Chronic Kidney Disease of Unknown Origin in Sri Lanka and its Relation to Drinking Water Supplies

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

D.G Amara Paranagama

BSc. MSc.

School of Civil Environmental and Chemical Engineering

College of Science Engineering and Health

RMIT University

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis/project is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

D. G. Amara Paranagama

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ABSTRACT

Chronic Kidney Disease (CKD) is a major health issue in North Central Province (NCP) of Sri Lanka. Anuradhapura and Polonnaruwa are the two most affected districts in NCP. This research was designed to identify possible causative agents of CKD in those two districts and to propose suitable harm minimisation techniques to counter CKD. Water quality parameters related to CKD were identified from literature. Drinking water samples were collected from drinking water sources of shallow wells of CKD patients and non-patients in Anuradhapura and Polonnaruwa districts and they were tested for chemical parameters of chloride (Cl^-), fluoride (F^-), nitrate (NO_3^-), phosphate (PO_4^{3-}), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), cadmium (Cd^{2+}) and arsenic (As^{3-}). Soil samples were also collected from the vicinity of drinking water wells and analysed for the same parameters. An analytical framework was developed to examine water quality of primary and secondary data using statistical methods namely, Univariate Analysis of Variance (ANOVA) and Dunnett's T3 post-hoc test, Kruskal-Wallis (KW) and Mann-Whitney's post-hoc test followed by Factorial and Discriminant analyses. ANOVA and Kruskal-Wallis tests with their post-hoc tests indicated significant differences in water quality parameters between sampling groups with respect to their mean and median values.

Factorial analysis results on CKD patient samples showed that sodium and fluoride pooled into a common factor which was significant and reliable at $p < 0.05$ and Cronbach's $\alpha > 0.7$ respectively. On the other hand in non-patient samples, sodium and fluoride as a combined factor was non-existent or less significant than magnesium and fluoride. Total results indicated that sodium and fluoride combination was the probable factor in drinking water of CKD patients. Factorial analysis results were compatible with group classifications according to Discriminant analysis. Literature suggests sodium fluoride (NaF) to cause acute and chronic kidney damage in experimental animals. Also fluoride toxicity to human kidney cells leading to CKD situations have been reported from other countries where similar groundwater fluoride levels exist. The results of primary and secondary data were also analysed for fluoride correlation with sodium percentage, alkalinity, calcium, pH and hardness in water. These results were indicative of fluoride in groundwater to be related to hydrogeology in the CKD endemic area. Even though Cd^{2+} and As^{3-} were suspected to be

causing CKD, As^{3-} was not detected in Anuradhapura and Polonnaruwa samples and Cd^{2+} was insignificant in Polonnaruwa samples.

Rainwater harvesting was proposed as a mitigation measure to the CKD endemic areas as an alternative to groundwater supplies. Rainwater tank estimations were carried out for eight rainfall stations in Anuradhapura and Polonnaruwa districts. Mass Curve analysis was carried out to estimate optimum tank sizes using recent ten years rainfall data. Dimensionless graph can be used as a tool to determine tank sizes which is specific to a given rainfall station. Dimensionless graphs were constructed for each rainfall station using daily and monthly rainfall data. Daily and monthly rainfall models showed significant differences in tank size estimations and daily models gave bigger tank sizes than monthly models for the same demand levels. The reason was that daily rainfall variations were also counted in daily models which were not accounted in monthly models. Thus it was concluded daily models were preferable over monthly models for tank estimation to the proposed areas. For a four member household with average 6 L/capita/day consumption, the rainwater tank sizes varied between 2900 and 5100 L in the eight rainfall stations. Minimum runoff surface area for each station was estimated to be between 6.7 to 18.2 m^2. Volumetric reliability of the estimated tanks were analysed for 60, 80 and 100% demands out of supply situations and results showed that volumetric reliability varied depending on tank size. Sensitivity analysis results showed that tank sizes were sensitive to runoff surface characteristics, household numbers and per capita consumptions. Estimated tank sizes were of manageable size and can be applied in Anuradhapura and Polonnaruwa districts at household levels to supply drinking water as an alternative to groundwater sources.

Removal of fluoride from drinking water obtained from groundwater sources was the other CKD mitigation technique proposed to the research area. Key criteria for the selection of natural adsorbents were low cost and availability of material in the CKD endemic area as well as simplicity of application at domestic level. Materials tested for fluoride removal were turmeric, ginger and curry leaves. Out of them turmeric powder showed the highest adsorption capacity and 20% removal at fluoride concentrations between 2 and 20 mg/L. Lab experiments were designed for characterization of turmeric powder to remove fluoride using batch and column experiments. To assess the adsorption mechanisms, batch test data

were applied to Freundlich and Langmuir Isotherms. Langmuir Isotherm was found better fitted to experimental data indicating monolayer adsorption. Kinetics of adsorption was examined using Lagergren pseudo first- and second-order kinetic models. Pseudo first-order kinetic model showed a better fit of experimental results. Intra-particle mass transfer diffusion equation indicated the adsorption which is governed by diffusion within the pores of the adsorbent contributing to the rate determining steps**.** Column experiments were used to assess the adsorption of fluoride on turmeric depending of flow rate, initial concentration of fluoride solution and column heights of turmeric powder. Using breakthrough analysis, model parameters for Bed depth service time (BDST model), critical bed depth, Bohart-Adams model and Tomas model were determined. Fluoride adsorption by turmeric could be attributed to the processes of ion-binding and ion-exchange between turmeric and fluoride. After column experiments turmeric was regenerated with 1.0M NaOH. With the test results it was concluded that turmeric powder is a potential material for effective removal of fluoride.

ABBREVIATIONS

Ache - Acetyl cholinesterase

ANOVA - Univariate Analysis of Variance

APHA - American Public Health Association

BDST - The Bed Depth Service Time

BGS - British Geological Survey

CBSL - Central Bank of Sri Lanka

CEA - Central Environmental Authority

CKD - Chronic Kidney Disease

CYN - Cylindrospermopsin

DA - Discriminant Analysis

DCYN - Deoxy-Cylindrospermopsin

DAPH - Department of Animal Production and Health

DMSL - Department of Meteorology Sri Lanka

EuC - European Commission

EC - Electrical Conductivity

EDA - Exploratory Data Analysis

FA - Factorial Analysis

GFR - Glomerular Filtration Rate

GI - Galvanised Iron

IEV - Initial Eigen Value

KMO - Kaiser-Meyer-Olin and Bartlett's

KW - Kruskal-Wallis

MAgri - Ministry of Agriculture

MCL - Maximum Contaminant Level

NHANES - National Health and Nutrition Examination Surveys

NIPHEP - National Institute for Public Health and Environmental Protection

NRC - National Research Council

NCP - North Central province

PV - Percentage Variance

PCA - Principal Component Analysis

RWH - Rain Water Harvesting

SIRKBP - Second Interim Report on Kala Oya Basin Comprehensive Plan

SMCL - Secondary Maximum Contaminant Level

SL - Sri Lanka

SLR - Sri Lankan Rupees

TDS - Total Dissolved Solids

TISAB - Total Ionic Strength Adjustment Buffer

TMV - The Muslim Vegetarian

TSP - Triple-Super Phosphate

TWDB - Texas Water Development Board

USEPA - US Environmental Protection Agency

USPHS - US Public Health Service

WHO - World Health Organization

WRBSL - Water Resources Board of Sri Lanka

SYMBOL LIST

A	Runoff surface area (m^2)
b	Langmuir adsorption constant (L/mg)
C	Consumption per capita per day in the household (L/capita/day)
C_B	Desired concentration of solute at breakthrough (mg/L)
C_e	Fluoride concentration at equilibrium (mg/L)
C_i	Initial fluoride concentration (mg/L)
C_o	Initial concentration of solute (mg/L)
C_t	Fluoride concentration at time t (mg/L)
D	Yearly water demand for all users in a household (L/year)
h	Bed depth (cm)
h_o	Critical bed depth (cm)
k_2	Pseudo second-order kinetic rate constant (g/mg/min)
k_a	Adsorption rate constant (mL/mg/min)
k_{AB}	Bohart-Adams model kinetic constant (mL/mg/min)
k_f	Freundlich constant
k_1	Lagergren pseudo first-order rate constant (min^{-1})
k_p	Intraparticle diffusion rate constant (mg/g/min)
k_{TH}	Thomas rate constant (mL/min/mg)
N	Number of people in household using water
n	Empirical parameter
N_o	Adsorption capacity per unit volume of adsorbent column (mg/L)
P	Annual depth of rainfall (mm/year)

q	Amount of fluoride adsorbed per unit mass of adsorbents
Q	Inlet flow rate (mL/min)
q_e	Fluoride adsorbed per unit mass of adsorbent at equilibrium (mg/g)
Q_o	Monolayer capacity of the adsorbent (mg/g) - Equations 5.4 and 5.5
q_t	Amount of fluoride adsorbed at any time t (mg/g)
R	Rainfall (mm/year)
$R(\%)$	Removal percentage of fluoride
R_c	Runoff coefficient of the catchment surface
R_p	Total runoff per year (rainwater harvesting potential) as a depth (mm/year)
$RWHP$	Rain water harvesting potential (m^3/year)
t	Time (min)
v	Volume of fluoride solution (mL)
V	Linear flow velocity (flow rate/column section area, cm/min)
W	Weight of adsorbent (g)

CONFERENCE PROCEEDINGS

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1 INTRODUCTION

1.1 Background

Chronic Kidney Disease (CKD) is a major health concern in Sri Lanka. North Central Province (NCP) in Sri Lanka reports the highest CKD patients with approximately 20,000 deaths in 20 years till 2011 (Fernando 2011). In 2009 approximately 5000 patients have been treated for CKD in NCP (WHO 2009) and in 2012 the patient number have further escalated to 8000 (WHO 2012).

In NCP of Sri Lanka, there are no large scale industries or industrial mines. Agriculture is the largest sector of employment with 51% of population involved in farming (CBSL 2010). Pipe water for drinking is available to only 16.4% of the population in NCP (CBSL 2010). As a result, the main drinking water requirements and other human consumptions of the affected rural communities are met from untreated groundwater sources (Perera et al. 2008).

In the CKD endemic areas of NCP, water from nearly 50% of the dug wells have been found with undesirable levels of fluoride (F^-) contributing to dental fluorosis especially in children (Padmasiri et al. 2012). A large number of studies have revealed fluoride contents in groundwater in CKD endemic areas above WHO (1993) recommended level of 1.5 mg/L (Dissanayake & Weerasooriya 1985, Dissanayake 1991, 2005, Herath et al. 2005, Bandara et al. 2008, Panabokke & Ariyarathne 2008, Perera et al. 2008, Chandrajith et al. 2010, Weeragoda et al. 2012, Dissanayake et al. 2012). Therefore, in this research fluoride levels in drinking water were further investigated as a potential factor influencing CKD in the disease endemic areas of NCP.

There are many studies to prove damage to kidney tissues by excessive and long-term exposure to fluoride in animals as well as humans (Kawahara 1956, Ramseyer 1957, Pindborg 1957, Manocha et al. 1975, Greenberg 1986, Lantz et al. 1987, Banu et al. 1997, Ando et al. 2001, Liu et al. 2005). Mercury (Hg), uranium (U), selenium (Se), lead (Pb) and arsenic (As^{3-}) are some other heavy metal nephro-toxicants which have been recognized to cause progressive renal disease even in small concentrations (Karmaus et al. 2008, Navas-Acien et al. 2009, Sunderland et al. 2010). Studies also show that dietary cadmium (Cd^{2+})

intake has an effect on kidney diseases (Kido 1995, Loganathan and Hedley 1996, Andrea & Claudio 2005, Navas-Acien et al. 2009, Ferraro et al. 2010). Triple-super phosphate (TSP) fertilizer imported for paddy farming in Sri Lanka have been found to contain arsenic, lead, mercury, cadmium and aluminium as impurities (Bandara et al. 2010). However, water from shallow wells in CKD endemic areas have been reported with arsenic, lead, cadmium, aluminium, zinc, copper and nickel levels below WHO permissible levels (Jayawardena et al. 2012, Wasana et al. 2012, WHO 2012).

With regard to other metal pollutants, aluminium has been suspected to cause CKD due to extensive use of aluminium utensil in Sri Lanka (Herath et al. 2005). Blue-green algae scientifically named as Cyanobacteria have been identified to produce “Cyanotoxins” (algal toxins) capable of causing both acute and chronic illnesses which affect liver and kidneys. Algae growing in open water in NCP also had been suspected to cause CKD but this theory had not been supported by any evidence (Pethiyagoda 2011).

Although researchers have explored various water quality parameters to determine impacts related to CKD, they are yet to converge on any definitive causative factors. The proposed research aims to seek this convergence and re-examines the previous research findings to identify possible causative agents of CKD.

This research was designed to identify the CKD causing parameters present in NCP of Sri Lanka. In this effort, the suspected CKD causing chemical parameters present in NCP were identified. Subsequently harm minimisation techniques were investigated in relation to the affected region. Rainwater harvesting was identified as a viable method to supply drinking water to the CKD affected areas as an alternative to groundwater sources. By analysing previous rainfall data for 10 years, rainwater tank sizes for the CKD endemic areas were estimated with catchment surface specifications. Also if the available groundwater is to be used for drinking, minimising fluoride level of water by natural adsorption was also investigated as a suitable harm minimisation technique.

1.2 Research questions

The research questions answered in this study are:

- What are the factors related to CKD in the disease endemic areas of Sri Lanka?

- How do those CKD causing factors arise in the disease endemic areas of Sri Lanka?
- How does CKD patient drinking water differ from CKD non-patients?
- What are the suitable harm minimisation techniques to control CKD?
- How can those suitable harm minimisation techniques be applied to the CKD endemic areas in Sri Lanka?

1.3 Aim and objectives of the study

Several studies have been carried out by different organizations and individuals and different theories have been put forward regarding the root causes for CKD in NCP of Sri Lanka. However the causes are yet to be adequately researched and proved. The current research aims to re-examine previous findings on possible causative agents of CKD. The research also investigates harm minimisation techniques suitable for the disease affected areas depending on the possible causes. Rainwater harvesting was one of the CKD mitigation measures proposed in this study. As such estimating rainwater tank sizes to CKD endemic areas of NCP was an objective as an alternative to existing uses of groundwater sources. The other CKD mitigation measure proposed in the study was drinking water filtration using cheap and locally available natural material to remove fluoride.

Therefore the specific research objectives can be stated as follows:

- To re-examine the various causative factors of CKD identified by previous researchers. Also to identify the main pollutants of drinking water which are suspected to cause CKD.

- Carry out field tests to classify drinking water samples from shallow wells in disease endemic areas as CKD patient and non-patient samples.

- Analyse water quality of the CKD patients and non-patients samples for selected chemical pollutants which may cause CKD. Also detect any suspected heavy metals in water samples which can cause CKD.

- Formulate an analytical framework to identify water pollutants and their inter relations to quantify the significance of each parameter which are suspected to cause CKD.

- Statistically analyse the field test data to identify the prevalence of the disease causing water pollutants.
- Identify suitable CKD minimisation techniques to the disease endemic areas.

1.4 Scope of the thesis

Field sample collection campaign was carried out in the CKD endemic areas of NCP in Sri Lanka. Water samples were collected from drinking water sources of shallow wells of CKD patients and non-patients in disease endemic areas. Control samples were collected from a CKD non-endemic area. Water samples were analysed for CKD causing chemical parameters. Water quality parameters related to CKD were identified based on previous studies. Water samples were collected from the CKD endemic areas of NCP. The chemical parameters analysed were chloride (Cl^-), fluoride (F^-), nitrate (NO_3^-), phosphate (PO_4^{3-}) calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+) and cadmium (Cd^{2+}). Some soil samples were also collected from the vicinity of drinking water wells and analysed for the same parameters. All samples were analysed by a nationally accredited analytical lab in Sri Lanka namely SGS Laboratories Pvt Ltd, Colombo. Temperature and pH values of water samples were tested in the field. Test Protocols used by the lab included: 3120 APHA 21st Ed for cadmium, sodium, magnesium and calcium; 4500 APHA 21st Ed for fluoride, chloride and total phosphates; 4500 APHA 21st Ed for nitride.

Different statistical techniques were applied to analyse sample data to identify the occurrence of the CKD causing pollutants. The levels of each chemical parameter were compared with World Health Organization (WHO) standards. Descriptive statistics were used to interpret each chemical parameter in sampling groups. The methods namely Analysis of Variance (ANOVA) and Kruskal-Wallis (KW) followed by post-hoc tests were used to identify the significant differences in chemical parameters among the sampling groups. Discriminant analysis (DA) was applied to identify the correct sampling categorization and Factorial Analysis (FA) was used to explain chemical parameters that have high correlations which combined into factors. As a next step a set of published data collected by Chandrajith et al. (2011a) was also analysed by the same analytical methods and the results were

compared to reach at an assertive conclusion. SPSS software was used in these statistical analyses.

After identifying the prevalence of the CKD causing pollutants, strategies were explored to mitigate and minimise the impact of CKD in the context of NCP of Sri Lanka. Rainwater harvesting was one of the mitigation methods proposed as an alternative source to groundwater. Rainwater tank sizes were estimated for the CKD affected regions of Anuradhapura and Polonnaruwa districts based on historical rainfall data. For determining the optimum tank sizes, Mass curve method was applied on both daily and monthly rainfall data. Using both daily and monthly rainfall data mass curves were plotted to prepare dimensionless graphs, which allowed households to estimate their required tank sizes for different demand levels. The performance of estimated rainwater tanks designed for Anuradhapura and Polonnaruwa were determined by reliability analysis. Sensitivity analysis of tank sizes was also estimated for different design parameters.

Finally use of organic adsorbents for fluoride removal from drinking water was specified as another CKD mitigation measure. Turmeric powder was identified as a low-cost adsorbent and lab experiments were carried out to study the efficiency of fluoride removal by turmeric powder.

1.5 Outline of the report

The main framework of the research is based on literature survey given in Chapter 2. It identifies the Chronic Kidney Disease (CKD), the common causes of this disease and factors influencing CKD worldwide. Then the problem of CKD in North Central Province (NCP) of Sri Lanka was identified. The factors influencing CKD in NCP were also discussed in detail on which the research methodology was developed to identify CKD causes. Rainwater use was proposed as an alternative to groundwater for drinking in the CKD endemic areas. The other proposal for CKD mitigation was the use of natural adsorbents to reduce fluoride levels in drinking water. In literature rainwater harvesting and fluoride removal techniques are discussed. In Chapter 3, the methodology was developed to identify CKD causing factors in NCP related to groundwater supplies. Methodology describes how the data were collected in the field and what statistical analysis techniques were applied in the research. Chapters 4

and 5 give the methodologies of rainwater tank size calculation and lab experimental procedures followed for fluoride removal, respectively. In Chapter 6, results of statistical analysis of water samples collected and results of the secondary data analysed are given. Results and discussions on CKD mitigation methods are given in Chapters 7 and 8. Results of rainwater harvesting tank calculations for selected rainfall stations in the CKD endemic areas were presented in Chapter 7 where tank estimations using daily and monthly rainfall data models were compared using dimensionless graphs. Reliability and sensitivity of the estimated tanks were analysed consequently. Fluoride removal from water using natural adsorbents is given in Chapter 8. A CKD minimization plan based on potential mitigation methods are described in Chapter 9. Conclusions were drawn in Chapter 10 on statistical analysis results of drinking water, rainwater harvesting and use of natural adsorbents for fluoride removal. Finally few plausible recommendations are put forward for further works also in Chapter 10. The references and annexures relevant to the thesis are given at the end of thesis.

2 LITERATURE REVIEW

This chapter discusses the literature on characteristics of Chronic Kidney Disease (CKD) and its causes. Fluoride pollution, heavy metal pollution and other CKD causes are discussed in detail. CKD patient statistics in North Central Province (NCP) of Sri Lanka along with socio-economic conditions of those populations in the endemic areas are discussed. Hydrogeology and fluoride pollution of NCP is presented in detail. Heavy metal pollution and other CKD suspected causes in NCP are also given in this chapter. Drinking water of CKD patients and non-patients were analysed in this research as a main research component. Different statistical procedures followed to analyse these data are introduced in this chapter. Rainwater harvesting (RWH) was introduced as a CKD mitigation measure. The present situation of rainwater harvesting and its pollution in Sri Lanka are discussed. Finally different fluoride removal techniques are discussed in this chapter.

2.1 Chronic Kidney Disease (CKD) and its causes

The kidneys are the principal excretion organs of human body which process nearly 200L of blood per day to remove excess fluids and waste products into urine. Kidneys play a major role in regulating minerals such as calcium, sodium, and potassium in the body and also produce hormones necessary for body function.

Chronic Kidney Disease (CKD) is known to develop gradually, taking months to years, frequently leading to permanent loss of kidney function over time. Harmful effects of CKD are accumulation of water, waste and toxic substances in the body which are excreted by the kidneys. The loss of kidney function is known to cause anaemia, high blood pressure, bone diseases and acidosis disorders (excessive acidity of body fluids) associated with cholesterol and fatty acids (Major 2012).

Glomerular Filtration Rate (GFR) is a blood test which is used to estimate kidney functions. This test gives an account of how much blood passes through glomeruli, in kidneys each minute. CKD has been divided into five stages (1 to 5) based on GFR values (Table 2.1). Out of them Stage 5 is named as Chronic Kidney Disease (CKD). It is also called Kidney Failure, End-stage Kidney Disease or End-stage Renal Disease. At this stage there is total or near-

total loss of kidney function with dangerous accumulation of water, waste, and toxic substances in the body leading to death of patients (Juncos & Donadio 1972).

CKD situation has reached epidemic proportions both in developed as well as in developing countries; however the majority of CKD patients receiving dialysis or transplantation of kidneys are reported to be in rich industrialized countries (Nwankwo & Ummate 2006). For example it has been projected the cost of renal replacement therapy to exceed 1 trillion dollars per annum globally at a patient per capita cost of over $55,000 in the US (Nwankwo & Ummate 2006).

Table 2.1 Stages of Chronic Kidney Disease (CKD)

Stage	Description	Glomerular Filtration Rate (GFR) mL/min/1.73 m^2
1	Slight kidney damage with normal or increased filtration	> 90
2	Mild decrease in kidney function	60-89
3	Moderate decrease in kidney function	30-59
4	Severe decrease in kidney function	15-29
5	Kidney failure	< 15

(Source: Juncos & Donadio 1972)

Toxic agents and their metabolites are subject to accumulation in the kidneys (in renal medulla) and therefore the kidneys are found to be prone to environmental toxins. Environmental risk factors associated with CKD have been categorized as physical factors which include radiation, heat, electromagnetic field and altitude; chemical factors such as heavy metals, solvents, hydrocarbons and environmental toxins; biological factors of bacteria, parasites, virus and fungi. These factors have also been categorized as airborne and waterborne depending on sources. Airborne environmental toxins have been commonly identified as gaseous compounds (commonly carbon monoxide, vinyl chloride and radon); vapour toxins (lead, mercury, arsenic, nickel) and dust toxins (asbestos, silica, cotton fibres, coal, air-born allergens). Waterborne factors are known to be microbial pollution of drinking water, or chemical contaminations (such as naturally occurring chemical substances which pollute groundwater supplies, heavy metals, toxic wastes, pesticides and agricultural chemicals). Water can become contaminated with harmful substances namely - heavy metals and organic or non-organic compounds leached from soil to cause CKD. Various

disorders directly or indirectly related to water are also named as waterborne factors of CKD. High temperatures leading to water scarcity in tropical regions is named as a waterborne factor and high-fluoride in groundwater found in many parts of the world is another water borne factor identified to cause CKD (BGS 2000, Dissanayake 1991).

2.1.1 Fluoride pollution

Literature suggests fluoride is an essential hardening component of bones and teeth (Juncos & Donadio 1972). However it is recently revealed to have no nutritive value and the previous assumptions to be based on natural calcium and fluoride correlation (Sauerherber 2013). Further to that, the main ingredients in teeth are not fluoride but hydroxyapatite that contains calcium phosphate. Fluorine is a highly reactive element leading the other chemical components in electronegativity and therefore not found in nature on its own (Sauerherber 2013).

The optimum fluoride level in drinking water for general good health set by World Health Organization (WHO) is between 0.5 and 1 mg/L and the maximum acceptable concentration is 1.5 mg/L as applicable to countries where people drink more water than average U.S. citizens (WHO 2006, Srimurali et al. 1998, Fan et al. 2003, Ghorai & Pant 2004, Ozsvath 2006). According to drinking water standards of US Public Health Service (USPHS 1962), the maximum allowable fluoride concentration in drinking water varies with maximum daily air temperature. In dry zone areas of NCP, the maximum daily air temperature is between 26.3–32.5°C. According to BGS (2000), the maximum allowable fluoride concentration in drinking water within that temperature range is 1.4 mg/L and the recommended lower and upper limits are 0.6 and 0.8, respectively.

Fluoride has become a controversy due to various research findings on their harmful nature to humans and animals. Long-term consumption of water with fluoride concentrations above 1 mg/L has been found to cause dental fluorosis and bone disease (Ozsvath 2006, Lv et al. 2013). According to Juncos & Donadio (1972), ingestion of fluoride levels above 1.5 mg/L has been found to cause dental and skeletal fluorosis in children and adults.

Countries which are towards the mid-latitude and arid regions are found to have fluoride in groundwater above maximum acceptable limits of WHO (WHO 2006). More than 20

developed and developing nations are found to have endemic conditions of fluorosis including Argentina, USA, Morocco, Algeria, Libya, Egypt, Jordan, Turkey, Iran, Iraq, Kenya, Tanzania, South Africa, China, Australia, New Zealand, Japan, Thailand, Canada, Saudi Arabia, Persian Gulf, Sri Lanka, Syria and India (Mameri et al. 1998). As such fluoride rich groundwater regions overlap with fluorosis endemic regions.

In groundwater, natural concentration of fluoride is known to depend on the geological, chemical and physical characteristics of the aquifer, the porosity and acidity of the soil and rocks, temperature, the action of other chemicals and the depth to wells (Meenakshi & Maheshwari 2006). Low calcium and high bicarbonate alkalinity in groundwater is found to favour high fluoride in groundwater (Hem 1959, Bulusu & Pathak 1980). According to Meenakshi & Maheshwari (2006), due to those factors, fluoride concentration in groundwater ranges below 1 mg/L to more than 35 mg/L. However surface waters generally report of fluoride levels < 0.3 mg/L unless they are polluted from external sources (Meenakshi & Maheshwari 2006). High-fluoride groundwater is associated with sodium and bicarbonate as dominant dissolved constituents, and calcium and magnesium as relatively low dissolved constituents. Such water types are found to have pH values >7.

Geologically fluoride exists as sodium fluoride (NaF) as a soluble compound. It also exists as calcium and/or magnesium fluorides (CaF_2, MgF_2) which are less soluble. According to Sauerherber (2013), CaF_2, and MgF_2 are not listed as toxic compounds due to founding of comparatively high lethal oral doses in mammals (LD_{50} – 3750 mg/Kg), however NaF and synthetic industrial fluoride compounds which lack calcium are listed as toxic. Sodium fluoride is commonly used in toothpaste and mouth rinses to prevent dental decay. Sodium fluoride and fluoro silicic acid (H_2SiF_6) are also added to public water treatment systems which make them the main dietary sources of fluoride (Sauerheber et al. 2013). As such drinking water is the major source of fluoride to the body contributing 75–90% of daily intake. The degree of adsorption of fluoride to body through gastro intestinal track is related to solubility of fluoride after ingestion. According to Sauerheber (2013) ingested fluorides form complexes with dietary calcium and iron, reducing the solubility, so individuals with higher blood calcium would be more resistant to fluoride toxicity. It is thus calcium ions can act as an antidote in fluoride poisoning.

Other sources of fluoride to humans include food and beverages. Consumption of black tea as a beverage is a source of fluoride to the body when it is consumed in excess (Malinowska et al. 2008). Fluoride contents are in the range of 0.95 to 4.73 mg/L in black teas, 0.7 to 1 mg/L in green teas and 0.26 to 0.27 mg/L in herbal teas (Yuwono 2005). Black tea is the main type consumed among the rural communities in Sri Lanka. Industrial emissions, drugs and cosmetics may also be sources of fluoride depending on their constituents.

Some commercial uses of NaF are found in pesticides, including fungicides and insecticides. Sodium fluoride is also used in various types of adhesives and glues where it acts as a poisonous substance (Sauerheber et al. 2013). Pindborg (1957) has found that NaF given to rats at a concentration of 226 mg/L for 21-28 days to cause damage to the kidney tubules. A number of past studies on NaF toxicity cited by Pindborg (1957) include Goldenberg (1921), Chaneles (1939), Smyth & Smyth (1932), Hauck et al. (1933), Phillips & Lamb (1934), Roholm (1937), Pindborg (1950), Bond & Murray (1952) and Ogilvie (1953). A much later research by Manocha et al. (1975) have shown 7.5 mg/L of NaF given each day for 100 days to rats to show morphological changes in its kidneys, while 1–5 mg/L fluoridated water given to monkeys for 18 months to show cytochemical abnormalities in its kidneys. Greenberg (1986) also found that mice exposed to fluorides between 7 and 25 mg/L/day, to show inflammatory responses in kidneys with changes occurring in three renal areas leading to vascular injury, parenchyma ischemia and fibrosis. More recent animal experiments to show harmful metabolic effects of NaF leading to kidney damage are by Bouaziz et al. (2005), Al-Omireeni et al. (2009), Sauerheber (2013), Giri et al. (2014) and Sandeep et al. (2014).

There are other animal studies to prove damage to kidney tissues by excessive and long-term exposure to fluoride (Ando et al. 2001, Liu et al. 2005, Sharma et al. 2010 and Shashi et al. 2002). Fluoride has also been found to influence kidney diseases in rats with diabetic condition (Banu et al. 1997). A recent study in Sri Lanka has shown fluoride-rich water (2.25 mg/L) given to rats for six months from Padaviya reservoir, which supplies irrigation water to high CKD prevalent areas in NCP, to develop interstitial nephritis conditions in 45% cases. The control areas which were given water from non-endemic Kandy Lake have developed these conditions only in 6.5% cases (Dissanayake et al. 2012).

Fluoride toxicity to humans is difficult to assess experimentally, however Ramseyer (1957) and Cittanova et al. (1996) have shown fluoride toxicity to human kidney cells. Dose-effect relationship of fluoride levels in water and CKD are reported by Lantz et al. (1987) where consumption of highly mineralized water containing 8.5 mg/L of fluoride has been observed to cause renal failure. In another study carried out in China (Liu et al. 2005), renal damage has been identified in children exposed to 2 mg/L fluoride in drinking water. Xiong et al. (2007) have also shown that drinking water fluoride levels over 2 mg/L can cause kidney dysfunction in children. Renal damage in children due to high fluoride concentrations in water has also been observed in Japan (Ando et al. 2001).

CKD patients are at an increased risk of fluoride poisoning due to reduced GFR which decrease the ability to excrete fluoride into urine. It increases the potential for fluoride accumulation in the skeleton which is called skeletal fluorosis (Hileman 1988, NRC 2006, Groth 1973, Harinarayan et al. 2006). Due to the decreased ability to excrete fluoride into urine, these patients are at risk of developing fluorosis at normal levels of 0.7 to 1.2 mg/L of fluoride (Bansal & Tiwari 2006). These patients are known to develop skeletal fluorosis even at 1 mg/L fluoride in the drinking water and a total daily intake of about 1.5 mg of fluoride is known to be the maximum acceptable intake amount for nephritic patients (Schiffl 2008). CKD patients have fourfold more risk of spontaneous bone fractures and skeletal fluorosis, at fluoride concentration of 1 mg/L in drinking water (Ayoob & Gupta 2006). Thus damaged kidneys increase the accumulation of fluoride, causing further damage to the kidneys, bones and other organs.

2.1.2 Heavy metal pollution

Heavy metals are trace components in our natural environment. They have received special attention in water pollution due to their strong toxicity even at low concentration. Heavy metal pollution may occur by direct discharges into air, water and soil. Damage to the kidneys is commonly caused by inorganic metallic compounds that are water soluble. For example exposures to both cadmium and lead have been identified as a joint factor to cause CKD in the general population (Sunderland et al. 2010, Navas-Acien et al. 2009). Other heavy metals known to cause kidney disease are mercury, uranium, selenium and arsenic. Evidence of CKD due to lead exposure have been observed in the United States and other

developed countries (Navas-Acien et al. 2009). Arsenic due to chronic exposure has also been found to cause slow progressive renal failure (Karmaus et al. 2008).

Herbicides, rodenticides and insecticides are sources of arsenic while some herbal preparations are also known to contain arsenic. Phosphate fertilizers manufactured from phosphate rocks are found to contain various toxic heavy metals namely arsenic, aluminium, cadmium, lead and mercury according to their origin. Cadmium is known to occur as an impurity in Zn mining. Cadmium and other toxic heavy metals can be building up in soil due to continuous application of phosphate fertilizers. Therapeutic forms of gold, bismuth and platinum are also known to cause nephrotoxicity leading to kidney failure (Karmaus et al. 2008).

Studies conducted in many parts of the world on dietary cadmium intake have shown that it could cause CKD even at low concentrations (Navas-Acien et al. 2009). A National Health and Nutrition Examination Survey (NHANES) have been conducted in 1999-2006 in the United States. Those participants who were exposed to chronic cadmium as an industrial and environmental pollutant have developed renal proximal tubular damage and reduced glomerular filtration rate (GFR) related to CKD (Ferraro et al. 2010). According to another investigation in the Kakehashi River basin in Ishikawa, Japan where cadmium exposed patients have shown significantly higher indicators of renal dysfunction compared to non-exposed patients (Kido 1995). Cadmium found in plants and animals are accumulated through food chains. As a results rice plants contaminated with cadmium have been found to cause CKD who consumed those rice (Andrea & Claudio 2005). In another study in New Zealand approximately 20% kidneys of grazing animals tested since 1988 have found to contain cadmium higher than the maximum permissible limits set by the New Zealand Department of Health. This has been caused by long-term application of cadmium containing phosphate fertilizers to pastures (Loganathan & Hedley 1997). Heavy metals including cadmium leaching to soil may transport slowly but eventually may lead to deterioration of groundwater (Kalis 2006). European Commission (EU) has proposed an EU-wide charge on cadmium fertilizers due to potential threat to consumers through food chains (Oosterhuis et al. 2000).

2.1.3 Other factors of CKD

Painkillers that contain ibuprofen, naproxen and acetaminophen have been found to cause interstitial nephritis (kidney inflammation) that can lead to kidney failure (Chauhan 2014). Allergic reactions or side effects of antibiotics like penicillin and vancomycin are known to cause nephritis and kidney damage. Accidents, injuries, some surgeries and certain radio contrast dyes used to monitor blood flow to the heart and other organs have also been found to damage kidneys or reduce blood flow to the kidneys, causing acute (sudden) kidney failure which leads to CKD at later stages. Having certain systemic lupus erythematous (a connective tissue disease), sickle cell anaemia, cancer, AIDS, hepatitis C, and congestive heart failure also have made people at high risk of CKD.

Rate of loss of renal function with CKD is known to be highly variable among individuals with the same underlying causes (Nwankwo & Ummate 2006, McClellan & Flanders 2003). Premature infants of less than 32 weeks gestation who have calcium deposits in nephrons have sometimes known to develop kidney problems later in life. Age is found as another factor since the kidney function reduces with age. Family history have been identified as another factor and CKD causing agents are known to be modulated by genetic susceptibility and other co-morbid conditions (Sunderland et al. 2010).

CKD causing factors have been directly or indirectly related to the environment and/or to the socio-economic standards of those susceptible. As an example it has been found that CKD patients reflect a close resemblance in ethnic background, bio-ecology and socio-economic standards in five North African countries (Barsoum 2003). An incident of environmental implications on CKD have been reported among Damietta residents in Egypt who depend on a stretch of river Nile as the only source of water, which have been heavily polluted by municipal wastes, industrial black spots and household rubbish where over 50% of consumers are found with kidney and liver problems (Kamel 2004).

Unidentified nature of CKD is also known to be common in some countries other than Sri Lanka. For example in the USA, 2.7 times higher incidences of CKD have been reported among African-Americans than White Americans. Among African-Americans nearly 50% of excess risk factors of CKD have been explained as modifiable factors, but the others have not been explained (Tarver-Carr et al. 2002). Most of the causes of CKD in developing

countries are known to be undetected due to lack of modern diagnostic techniques. Thus a large percentage of patients, especially in the developing countries are known to have CKD due to unknown causes (Nwankwo & Ummate 2006).

2.2 CKD estimates in Sri Lanka

Endemic occurrence of a kidney disease has been recognized in NCP of Sri Lanka since 1990 (Athuruliya et al. 2009). The number of patients in 2012 has been estimated to be around 15,000 (Johnson et al. 2012). Sri Lanka is divided into nine major administrative divisions namely Provinces. Among them North Central Province (NCP) reports the highest number of CKD patients in the country. NCP consists of two districts namely Anuradhapura and Polonnaruwa. Anuradhapura reports the highest number of CKD patients and mortality rates among all the districts in the country while Polonnaruwa is secondary to Anuradhapura (WHO 2009). The number of death and live discharges of patients from 2000 to 2006 in Anuradhapura and Polonnaruwa districts are shown in Figure 2.1 (Poulter & Mendis 2009). In further refining the prevalence areas, Medawachchiya, Padaviya and Nikawewa divisions in Anuradhapura district and Medirigiriya division in Polonnaruwa district gave higher patient numbers than other divisions in these districts (WHO 2009). Apart from NCP, CKD patients have also been identified in Dehiattakandiya division in Eastern Province and Girandurukotte division in Uva Province (Figure 2.2). CKD prevalence has been negligible or almost zero in Central and Southern provinces (Chandrajith et al. 2010). In CKD prevalence divisions, there was more than one CKD patient in some households. Also households with CKD patients were observed to be scattered (about 100 m from each other). Due to localised nature of patient distribution, Chandrajith et al. (2011b) have suggested the causative factors of CKD to be related to environment and/or genetic.

In 2001, there had been 184 CKD deaths In Anuradhapura District Hospital (Table 2.2) which is the main tertiary care hospital of NCP, making CKD the leading cause of mortality (Hittarage 2004). For Anuradhapura, Polonnaruwa and the whole country in 2007, CKD had been the 1st, 2nd and 9th leading cause of death respectively (Fernando 2011). CKD numbers in NCP has nearly doubled during the period of 1990 to 2007 and the death rate has risen from 2.6 to 9.1 per 100,000 of population (Wijewickrama 2011). However it is apparent that the exact statistics for CKD patients are not definite in Sri Lanka. Barsoum

(2003) stated this is the usual situation for most developing countries as causes of CKD are very uncertain to isolate.

In terms of gender share in 2003, it was about three times more male than female (Table 2.3) among the CKD patients registered in Anuradhapura General Hospital (Hittarage 2004). However, according to WHO (2012), a higher occurrence of CKD is reported in females than males, yet more severe conditions found in males.

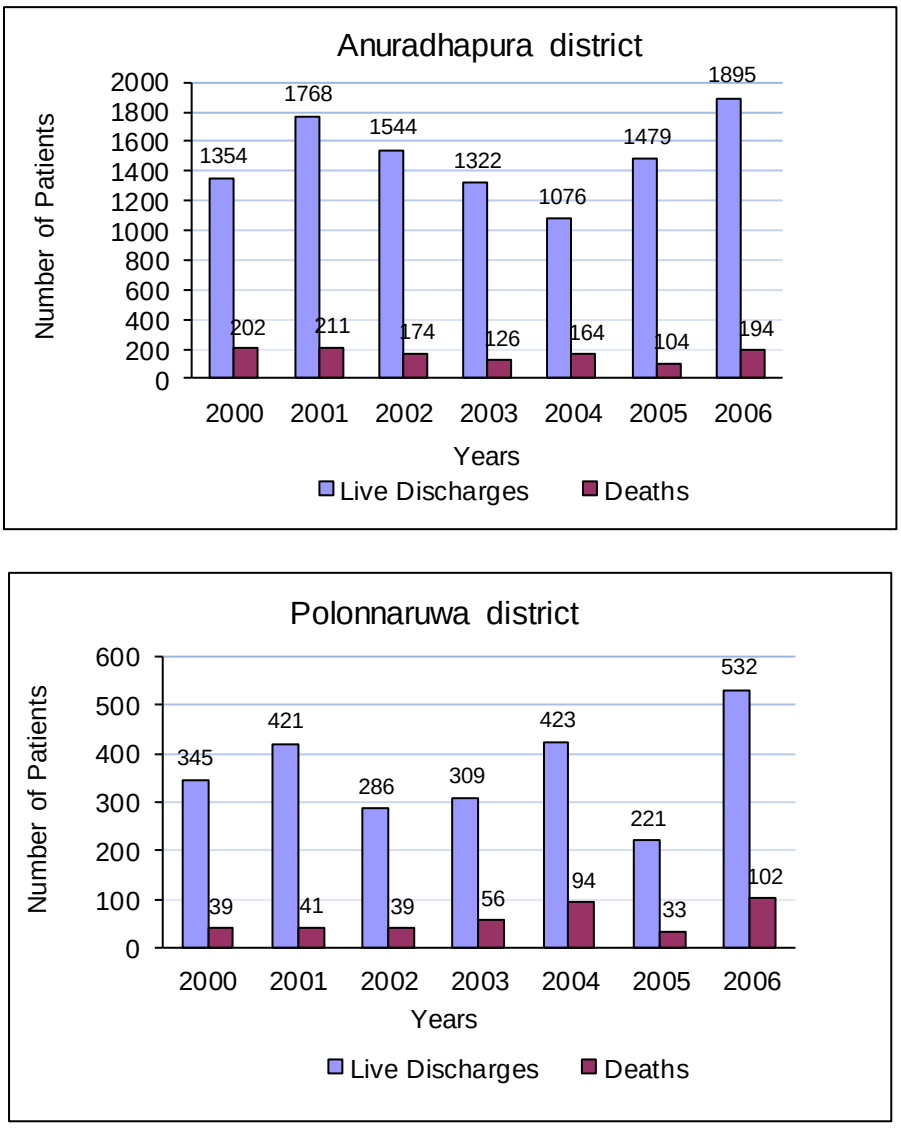


Figure 2.1 Number of CKD patient deaths and live discharges between 2000 and 2006 in Anuradhapura and Polonnaruwa districts

(Source: Poulter & Mendis 2009)

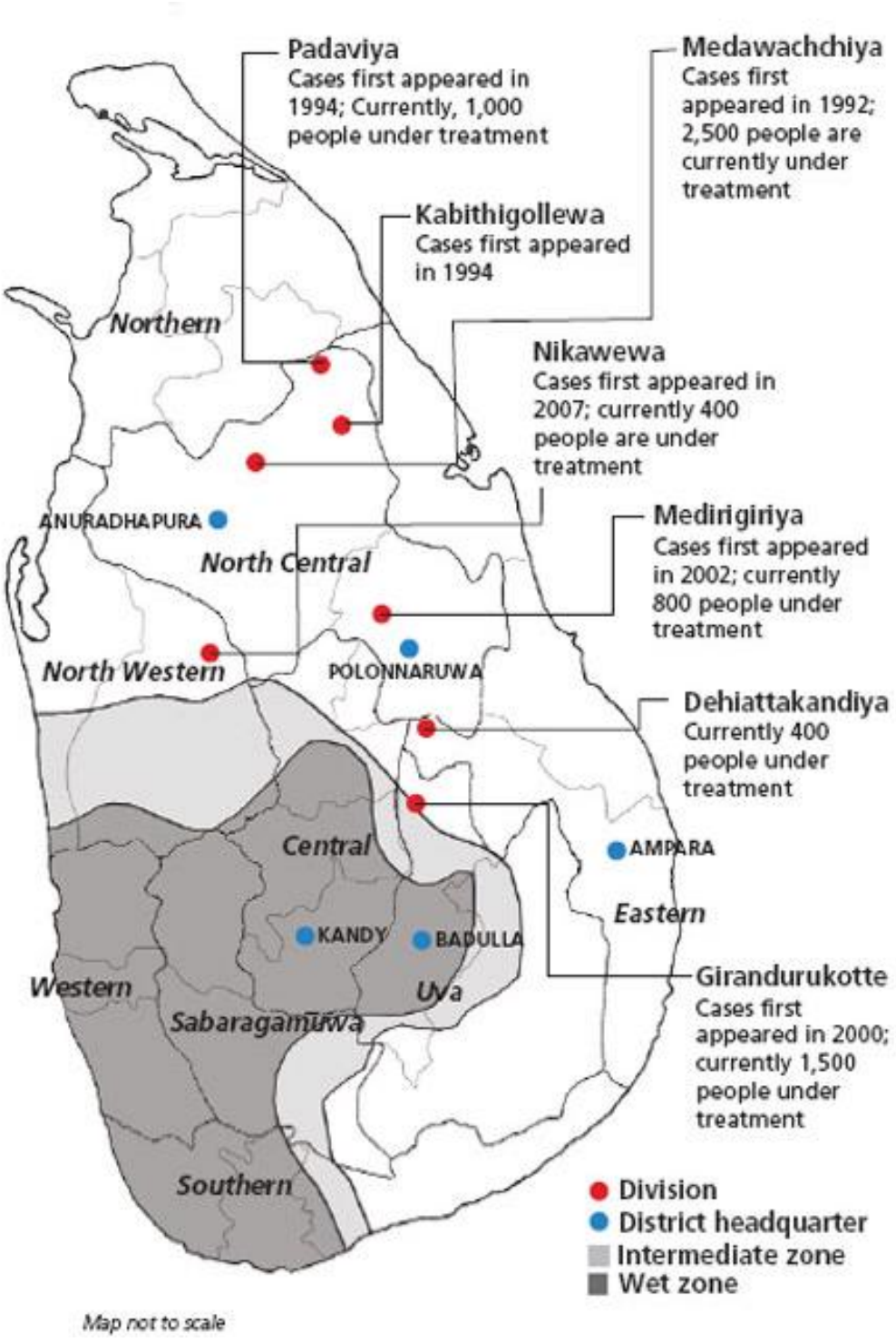


Figure 2.2 Areas with highest CKD patients in Sri Lanka

(Source: Sabnis 2012)

In 2003 about 76% of the total number of CKD patients (Table 2.4) had been above 50 years in Anuradhapura district (Hittarage 2004). WHO (2012) reported higher prevalence of CKD in both males and females above 39 years and a more recent estimate showed that 84% of the CKD patients in Medawachchiya division of Anuradhapura were above the age of 50 years (WRBSL 2013).

According to a clinical survey, major causes of CKD identified in patients from Western and other regions were diabetic nephropathy, hypertension, glomerulonephritis and obstructive uropathy whereas the causes related to about 27% of CKD patients in NCP had been unidentified (Goonerathne et al. 2008). According to WHO (2012), out of 1997 registered CKD patients, 775 (39%) have been identified with CKD of unknown origin, and other causes were hypertension (798, 40%), hypertension and diabetes (118, 6%), diabetes (90, 5%), obstructive uropathy (32, 2%), glomerulonephritis (30, 2%), polycystic kidney disease (10, 1%) and other known causes (18, 1%). In the patients with CKD of unknown aetiology, kidneys have shown tubule-interstitial nephritis condition suggesting that the cause could be of toxic aetiology (Dissanayake et al. 2012).

Table 2.2 Mortality records in the General Hospital of Anuradhapura in the year 2001

Leading cause of mortality	Death	Leading cause of mortality	Death
Chronic Renal Failure (CRF)	184	Heart Failure	36
Myocardial Infarction	115	Diabetes	18
Cerebral Vascular Accidents	114	Chronic Lung Disease	32
Pesticide Poisoning	102	Snake Bites	8
Alcoholic Liver Disease	72	Malaria	5
Oleander Poisoning	38	Viral Encephalitis	4
Pneumonia	81		

(Source: Hittarage 2004)

Table 2.3 Gender ratio of CKD admissions due to CKD in the year 2003 in Anuradhapura General Hospital

Male	Female	Total
250 (74.9%)	84 (25.1%)	334 (100%)

(Source: Hittarage 2004)

Table 2.4 CKD patient age distribution in Anuradhapura General Hospital admission register in the year 2003

Age group	Number	Percentage
10-19	1	0.3
20-29	3	1.0
30-39	24	8.1
40-49	43	14.5
50-59	77	26.0
60-69	68	23.0
70-79	68	23.0
> 80	12	4.1
Total	296	100.0

(Source: Hittarage 2004)

2.3 CKD related to hydrogeology in Sri Lanka

A mountainous area located towards south-central of the Sri Lanka, rises up to 2,524 m. A vast coastal plain surrounds this mountainous area. The central mountains are the source of over one hundred major rivers which flow across the lowlands to the Indian Ocean. Sri Lanka is divided into three major climatic divisions depending on yearly rainfall namely wet, intermediate and dry zones (Figure 2.3). Over two thirds of the land in Sri Lanka falls within the dry zone which receives an average annual precipitation of 1000–1500 mm as shown in Figure 2.4, predominantly from monsoonal rains (DMSL 2012). Dry zone area is mainly composed of flat lands with elevations of 100–400 m above sea level. Hydrogeologically NCP falls within low plain area of the dry zone.

In Sri Lanka nearly 70% of the land use is under agriculture (Kendaragama & Bandara 2000). Small-scale farming is commonly practised which provides daily consumption and a source of income. Seasonal crops such as green grams, corn as well as vegetables are commonly cultivated; however rice is the major cereal crop occupying nearly 50% of the total agricultural land (MAgri 2014a & 2014b). Scarcity of water for farming is a major problem faced by village communities in non-rainy periods. As a solution rivers starting from the central highlands of Sri Lanka are diverted to provide irrigation water to dry zone including NCP through reservoir and canal systems. In Anuradhapura district there are 400-500 small reservoirs functioning in 280 separate cascade systems, which exist as micro catchments to

carry water to rice fields from upper to lower elevations (Young et al. 2011). While this water helps farmer communities with irrigation supply, groundwater sources are benefitted from seepage of these cascade systems as well (Panabokke 2002).

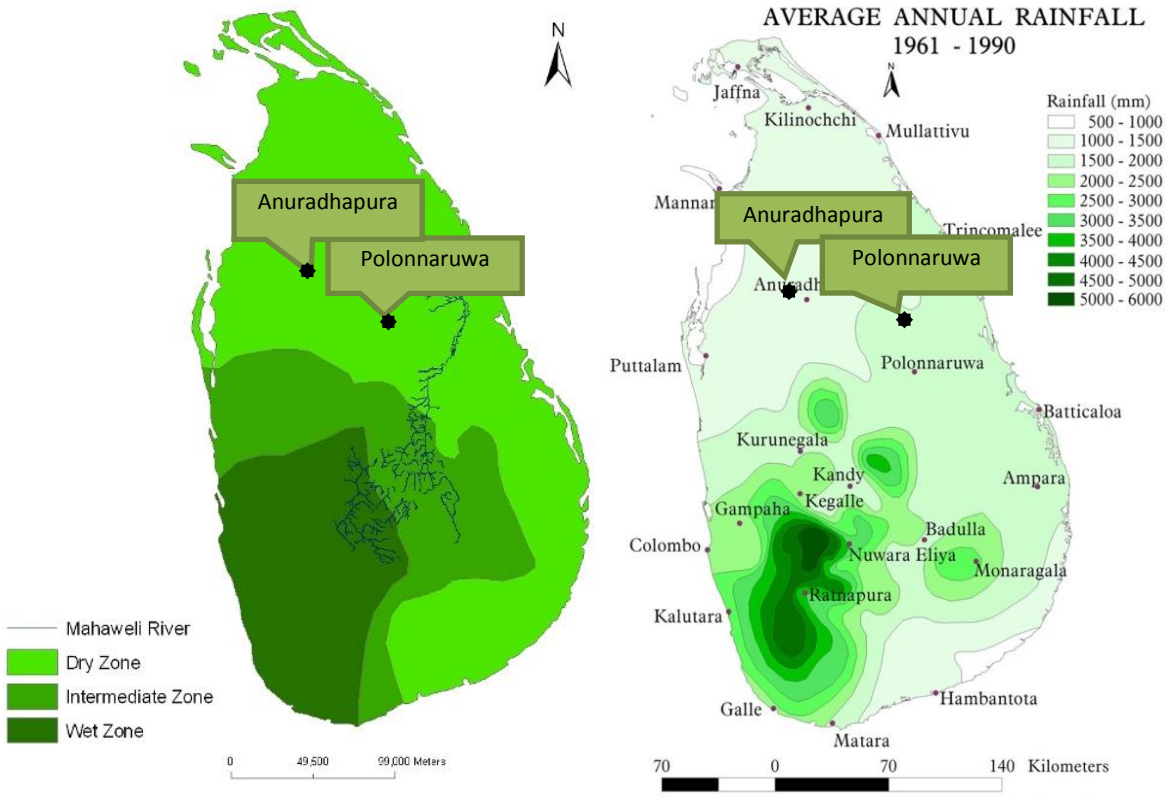


Figure 2.3 Average annual rainfall and climatic zone classification of Sri Lanka
(Source: DMSL 2012)

Agro wells are also being used to provide irrigation water in NCP during water scarce periods. A total of 15,000 agro wells of 5-10 m deep and 5-7 m diameter exist in NCP which get water from shallow regolith aquifers of hard metamorphic rocks (Panabokke 2002). It is estimated that the optimum number of agro wells that could be installed in NCP is approximately 3600, as such they have far exceeded the abstract limit of groundwater sources by over extraction (Panabokke 2002). As a result, groundwater levels have been lowered to the level of bed rock in limited supply areas (Panabokke 2002).

Groundwater sources in NCP are mainly of two types. The shallow regolith aquifers which are confined to narrow inland valleys are one type. These are in weathered zones and do

not get fed from a single continuous water table. Rather they exist as separate pockets having limited potential due to poor transmissivity of the underlying crystalline basement. These aquifers generally range between 2 and 10 m in thickness (SIRKBP 2002). These aquifers are traditionally being used to extract water for drinking and other household purposes using hand dug wells with depths of 1-10 m. Other water sources are in deeper fractured zones at depths more than 30-40 m (Young et al. 2011). Thus both shallow and deep wells are the sources of portable water in the CKD affected regions on NCP (Chandrajith et al. 2012).

More than 90% of the Sri Lankan landmass is underlain by Precambrian high-grade metamorphic rocks while a strip on north consists of limestone. Precambrian land mass is divided into four lithological complexes namely Highland, Vijayan, Kadugannawa and Wanni (Figure 2.4) (Cooray 1994). Anuradhapura consists of Wanni complex; its different geological formations are shown in Figure 2.5. On the other hand Polonnaruwa belongs to both Wanni and Vijayan complexes which consist of mainly biotite hornblende gneisses, scattered bands of metasediments, charnockitic gneisses and granites (Chandrajith et al. 2012). Fluorite, tourmaline and topaz are some other minerals found in NCP (Chandrajith et al. 2010). They all are identified as fluoride-bearing minerals which contribute to the general geochemical cycle of fluorine (Dissanayake 1991, Chandrajith et al. 2010, Chandrajith et al. 2012).

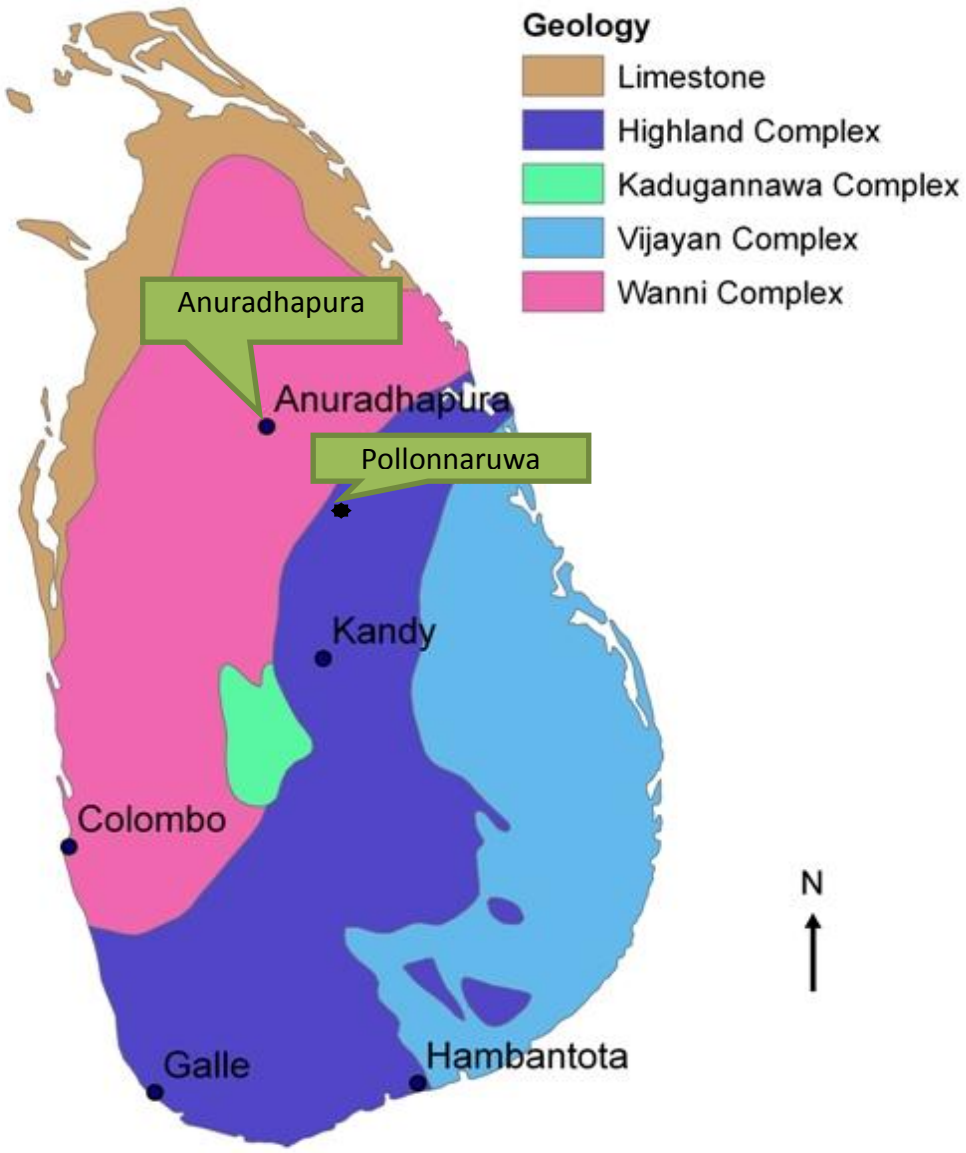


Figure 2.4 Map of the geological classification of Sri Lanka
(Source: SL 2014)

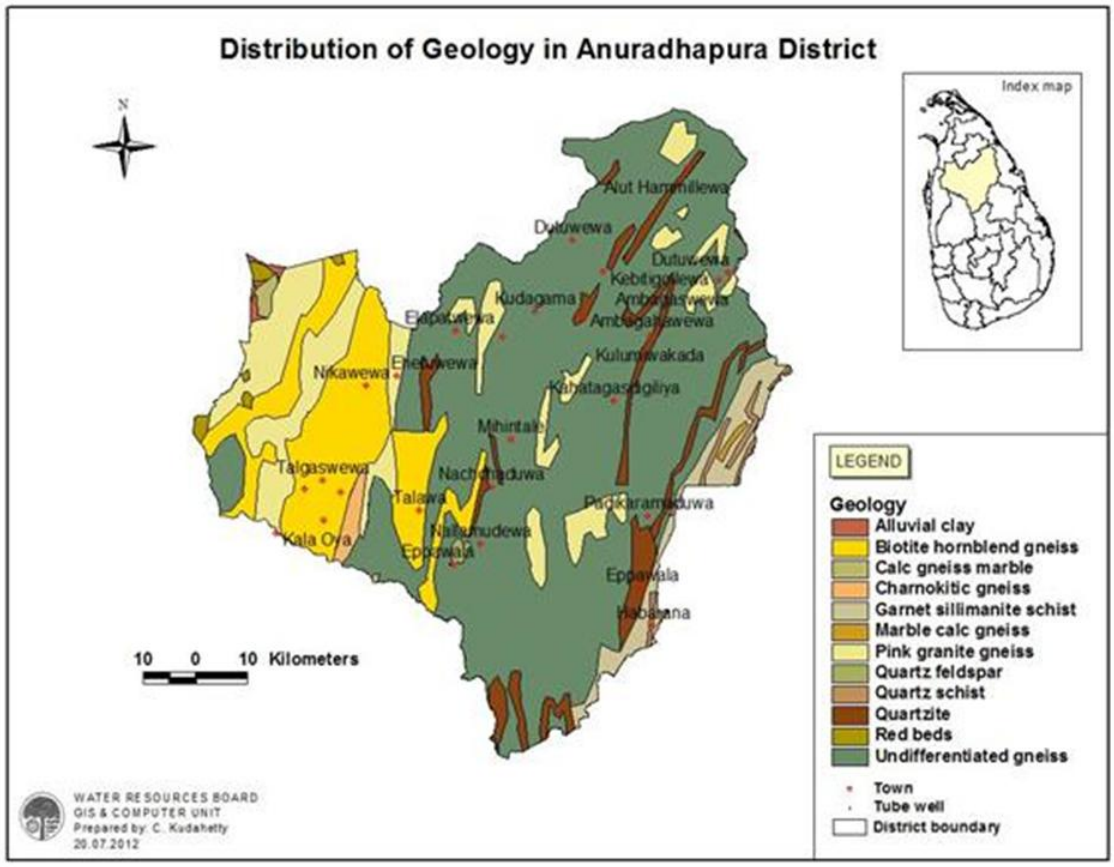


Figure 2.5 Distribution of geological formations in the CKD affected Anuradhapura district (Source: WRBSL 2013)

2.4 Fluoride pollution related to hydrogeology of NCP

According to Dissanayake (1996) high CKD prevalence areas are known to overlap with high groundwater fluoride areas in NCP. High fluoride levels above maximum acceptable limits in drinking water of NCP have also been proven with the number of incidences of dental and skeletal fluorosis (Dissanayake 1991). According to the Hydrogeochemical Atlas of Sri Lanka as shown in Figure 2.6, the wet zone of the country has average fluoride levels below 0.1 mg/L and the dry zone including NCP has fluoride levels between 1 and 3 mg/l (Dissanayake & Weerasooriya 1985). Perera et al. (2008) have shown 40% wells in NCP to have fluoride levels between 0.78 and 2.68 mg/L.

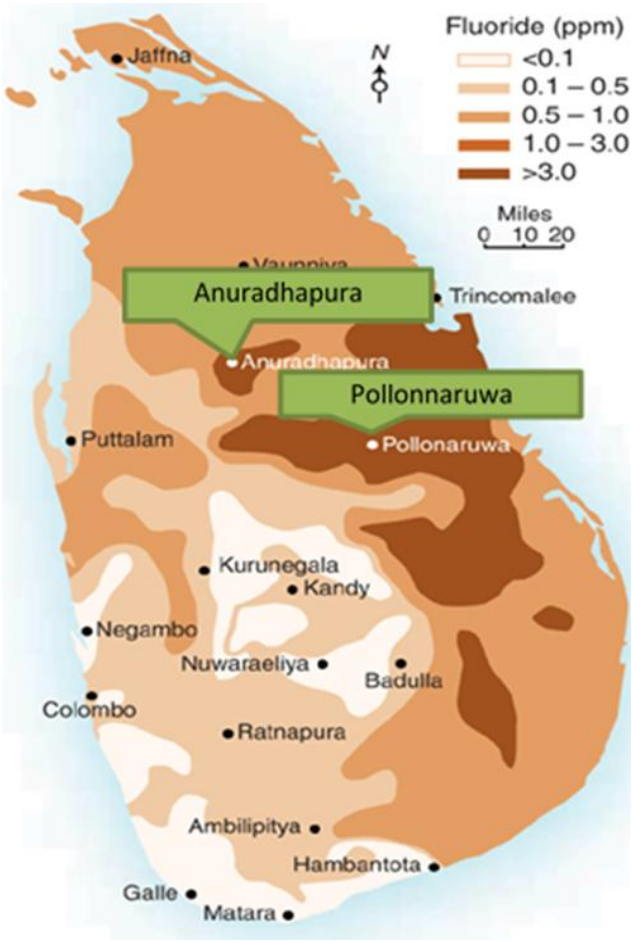


Figure 2.6 Fluoride distributions in groundwater in Sri Lanka according to Hydrogeochemical Atlas of Sri Lanka

(Source: Dissanayake & Weerasooriya 1985)

In Anuradhapura district, Eppawala subdivision has been found to contain as high as 9 mg/L of fluoride (Dissanayake & Weerasooriya 1985). According to Herath et al. (2005), some locations in NCP have been identified with fluoride concentrations in the range 1-4 mg/L with a median of 1.3 mg/l. According to Chandrajith et al. (2011a) fluoride concentrations in the CKD endemic areas in Anuradhapura district are between 0.02 and 5.3 mg/l and in non-endemic areas between 0.02 and 2.2 mg/L. Fluoride variations according to some of those research findings are given in Figure 2.7. A range of water quality parameters investigated by different researchers are shown in Table 2.5. According to a more recent study (WRBSL 2013) in one of the highly CKD endemic sub division of Medawachchiya in Anuradhapura, mean fluoride levels have been over 1.0 mg/L, in both shallow and deep groundwater (Figure 2.8 and Figure 2.9). According to Panabokke & Ariyaratne (2008) some dug wells in Anuradhapura district have been found with fluoride concentrations as high as 8 mg/L but in some wells located only 300 to 400 m away have fluoride levels less than 1 mg/L. The

variability of fluoride levels can be due to a range of geological factors including fluoride leachability from underlying rocks into groundwater (Herath et al. 2005).

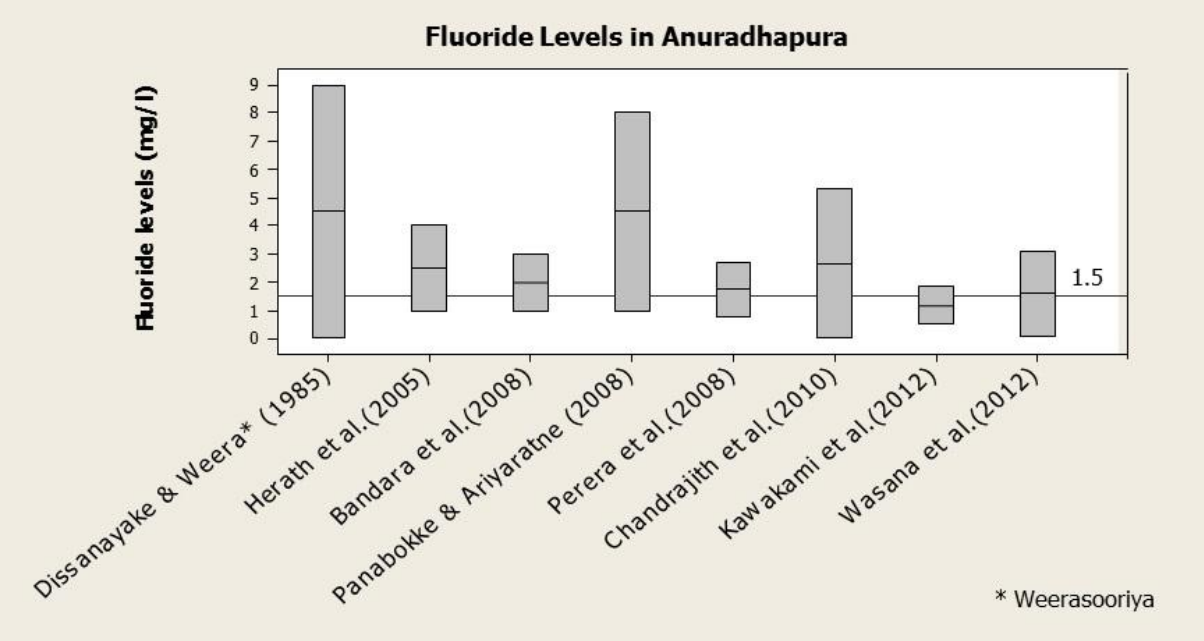
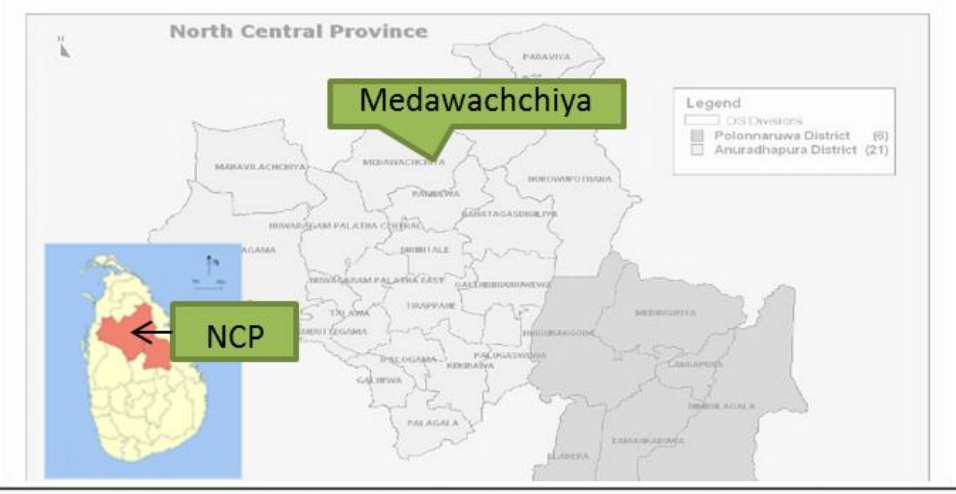


Figure 2.7 Variations of fluoride concentration in Anuradhapura according to different research findings

High fluoride in worldwide groundwater has been reported in crystalline basement aquifers and in arid sedimentary basins (Edmunds & Smedley 2005). In NCP too high fluoride levels in groundwater aquifers are also associated with fractured crystalline bedrock (Rao 2003 cited by Young et al. 2011). Traditional hand dug wells in NCP which are excavated below the weathered rock, enable fluoride bearing minerals to leach out and enrich water with fluoride (Herath et al. 2005). For example biotites underlay CKD affected divisions of Medawachchiya and Nikawewa which have an average fluoride of 0.08-3.5% by weight (Dissanayake 1991). Furthermore in Anuradhapura district high fluoride incidences have been correlated with the underlying fluoride bearing minerals of charnockites, charnockitic gneisses, granitic gneisses and hornblende gneisses (Dissanayake 1991) as shown in Figure 2.5. Other fluoride bearing minerals found in this region include micas, pyroxene, hornblende fluorite, tourmaline, topaz, sphene and apatite (Young et al. 2011).



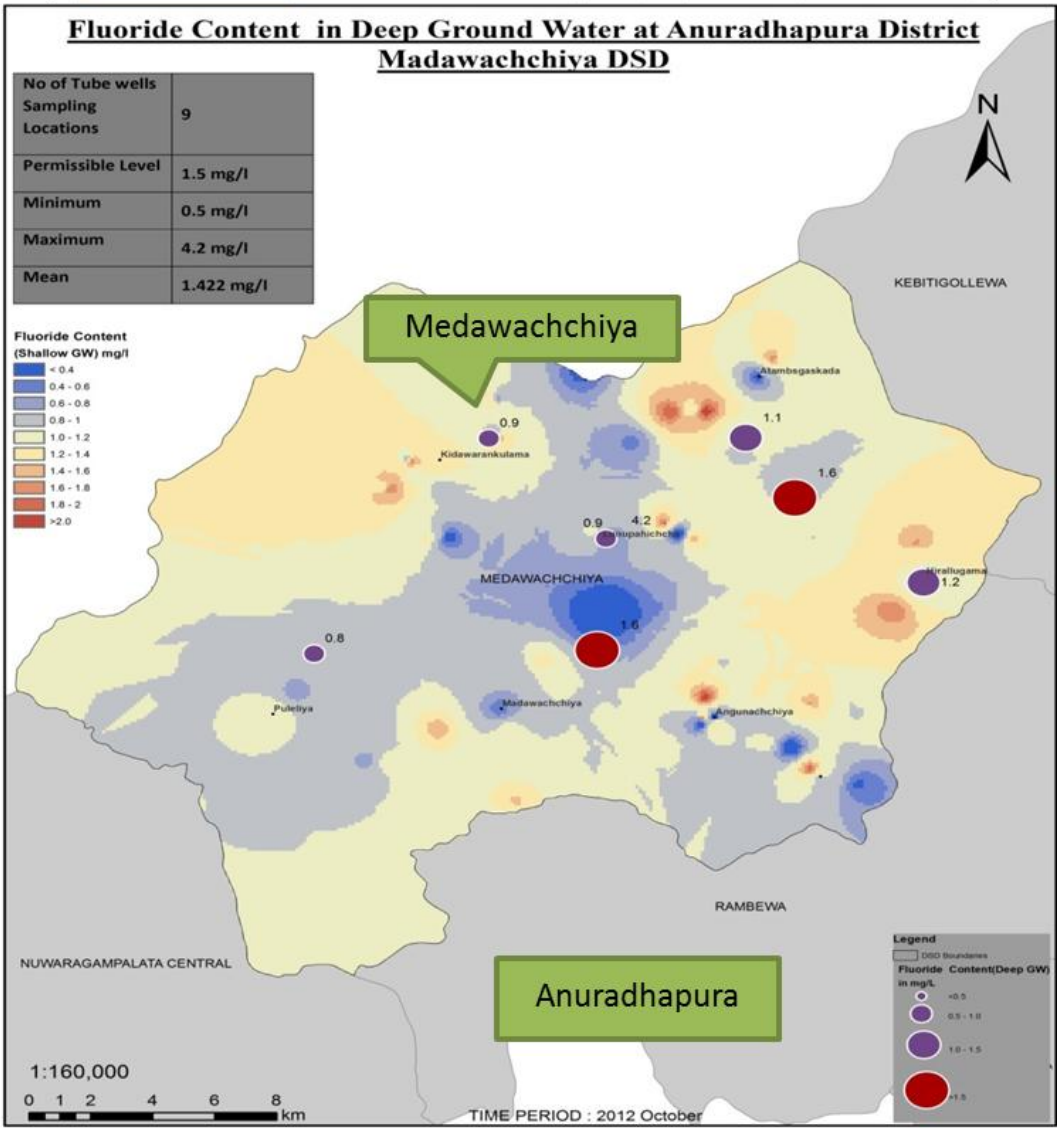


Figure 2.8 Fluoride levels in deep groundwater in sampling area of Medawachchiya in Anuradhapura

(Source: WRBSL 2013)

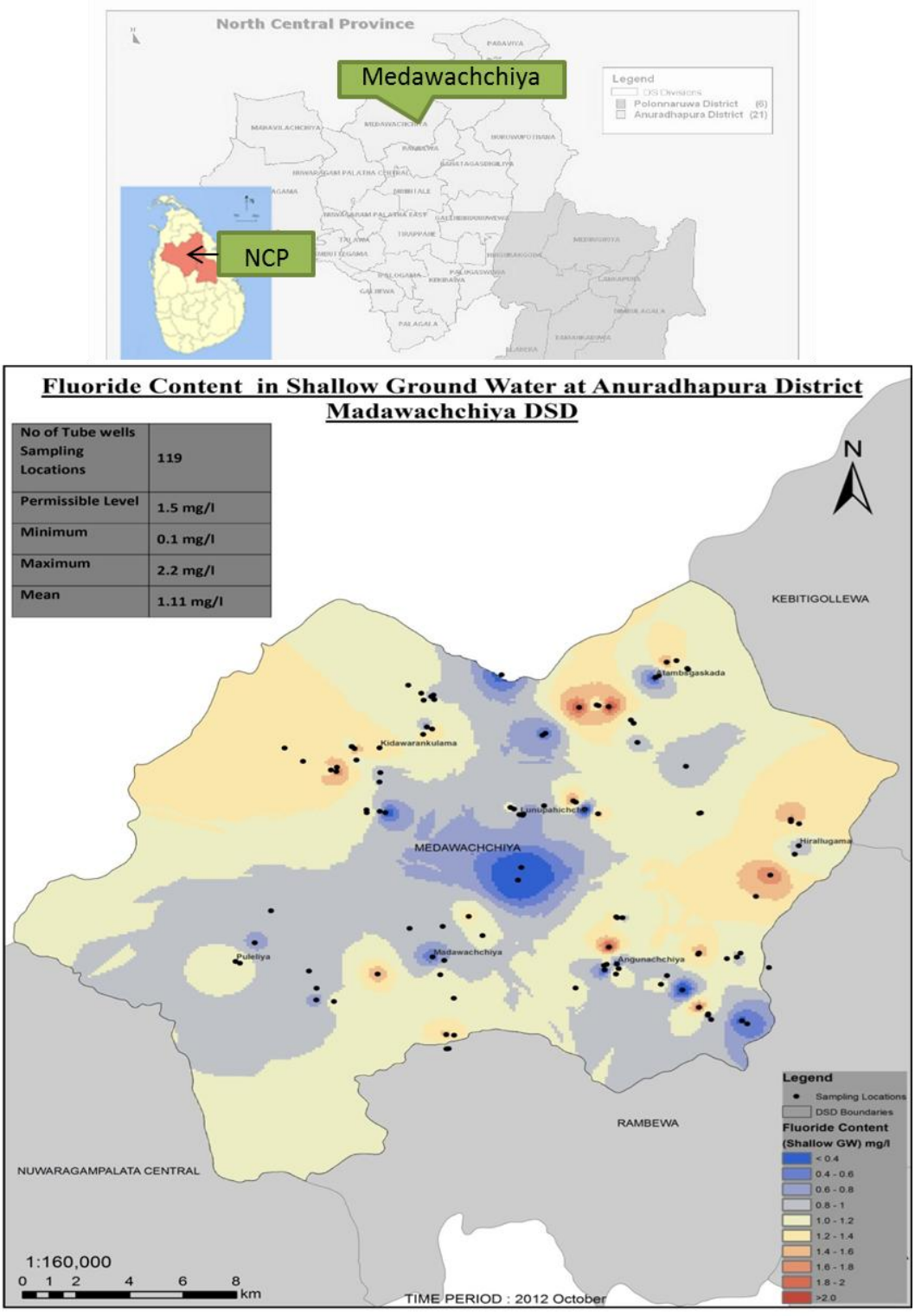


Figure 2.9 Fluoride levels in shallow groundwater in sampling area of Medawachchiya in Anuradhapura

(Source: WRBSL 2013)

Table 2.5 Water quality parameters in the CKD endemic areas of Sri Lanka

Parameter (mg/L except pH and EC)	WHO (2009)	Chandrajith et al. (2011a)	Chandrajith et al. (2011b)	Bandara et al. (2008)	Kawakami et al. (2012)	Wasana et al. (2012)
pH	9.2	-	8.1	-	-	-
EC µS/cm	-	-	3400	-	-	-
Alkalinity	500	-	684	-	-	-
Hardness	500	-	1921	-	-	-
Cl^-	250	-	688	-	-	-
NO_3^-	10	-	25.60	-	-	-
SO_4^{2-}	400	-	560	-	-	-
F^-	1.5	-	5.3	-	-	3.27
PO_4^{3-}	5	-	8.4	-	-	-
Na^+	200	-	1910	-	-	-
K^+	-	-	31.6	-	-	-
Ca^{2+}	200	-	256	-	-	-
Mg^{2+}	150	-	1280	-	-	-
Fe^{+3}	-	-	1.14	0.3	-	-
Mn^{2+}	0.1	-	0.7	0.05	-	-
Cd^{2+}	0.05	< 0.031	-	0.03	-	-
Pb	0.01	0.000957	-	0.01	-	-
Al	0.2	0.1922	-	-	-	-
Ni	-	0.006388	-	-	-	-
Cu	1.0	0.006414	-	-	-	-
Zn	5.0	0.09281	-	2	-	-
As^{3-}	0.05	0.005353	-	-	0.0003	-
U	-	0.002328	-	-	-	-
Co	-	0.000470	-	-	-	-
Cr	0.05	-	-	0.05	-	-

There are many factors explained to enhance fluoride levels in groundwater related to geography and hydrogeology of a given area. According to Ozsvath (2006), the maximum concentration of fluoride in groundwater is related to solubility of fluorite (CaF_2) leading to an inverse relationship between groundwater fluoride and calcium. Longer residence time in aquifers within fractured crystalline bedrocks may also enhance fluoride levels in the groundwater, which indicates a correlation between well depth and fluoride concentration (Young et al. 2010, Edmunds & Smedley 2005). As such fluoride in groundwater has been related to leachability of source mineral (Gaus et al. 2002, Ozsvath 2006). Another factor explained by Dissanayake (1991) and Chandrajith et al. (2010) is the climatic conditions of the area where warmer climatic conditions influence the leachability of fluoride bearing minerals of the soil. However leachability of fluoride from primary and secondary sources is

found to be higher under the effect of high rainfall (Dissanayake 1991). However wet zone in Sri Lanka have lower fluoride levels and is free from CKD whereas dry zone receiving less rainfall but turns out to be CKD endemic area. This phenomenon is explained by Dissanayake (1991) as evaporation bringing the soluble ions upwards by capillary action due to high ambient temperature (between 25-35°C). Also the low dilution effect is going to increase the groundwater fluoride concentration at pockets. This can be related to the fluorosis situation associated to CKD endemic areas in Sri Lanka where Community Fluorosis Index (CFI) is linked to the mean annual temperature of the regions.

Karthikeyan et al. (2000) have found a positive correlation between alkalinity and fluoride due to release of hydroxyl and bicarbonate ions during the leaching and dissolution processes of fluoride bearing minerals into the groundwater. The higher concentrations of fluoride and sodium ions are due to solubility of sodium fluoride compounds in water. Dissolved fluoride concentration is explained to be positively related to soft alkaline groundwater of sodium bicarbonate type chemistry and low calcium content (Edmunds & Smedley 2005, Hem 1959, Bulusu & Pathak 1980).

Furthermore volatiles found in the deep seated fractures and ligaments are also known to act as a source of fluorine (Dissanayake 1991). A number of lineaments with lengths varying from 1.25 – 100 km are found in an area of 30000 m^2 in Highland and Vijayan complexes of NCP which supports this phenomenon (Dissanayake 1991). Furthermore granites rich in fluorides are also reported in Vijayan complex (Dissanayake 1991).

Leachability of fluoride ions from carbonates are dependent on pH of draining solution which increases the solubility at pH values greater than 8.0, alkalinity, dissolved CO_2 and PCO_2 in the soil (Dissanayake 1991).

Intensive irrigation in the dry zone areas is another factor suggested to cause leaching of fluoride from the soils and weathered rocks (Chandrajith et al. 2011b). At the same time lower fluoride levels in some locations of NCP, is explained as groundwater mixing with fluoride free irrigation water that originate from central highlands of Sri Lanka (Chandrajith et al. 2010).

Due to the localized nature of the fluoride content variation in the CKD endemic areas of Sri Lanka, further related causes of CKD have been investigated by Chandrajith et al. (2011b). They have found comparatively lower Na/Ca ratios in the range of 1.6 to 6.6 in the CKD patient areas compared to ratios of 34 to 469 in the non-patient areas. According to these authors, increased Na/Ca ratio in water is favourable for the association of fluoride (F^-) and sodium (Na^+) ions to form complexes. In NCP, sodium concentration in agro wells has been identified with an average range of 15.5-221.5 mg/L (Kendaragama 2000). Also some wells in Northern Province of Sri Lanka (adjacent to NCP) have been reported with 100-280 mg/L (Nagarajah et al. 1989). Ayres & Wescot (1985) have reported 14% of the agro wells in dry zone exceeded the level of 440 mg/L (maximum recommended limit of sodium by WHO is 200 mg/L).

In Sri Lanka water from some of the shallow wells are associated with a taste associated to hardness. Hardness in natural drinking water is associated with calcium and magnesium. The maximum desirable level of calcium in drinking water is 100 mg/L while maximum permissible level is 240 mg/L (Perera et al. 2008). However it has been argued that according to the Sri Lankan standards the maximum desirable level of total hardness is 250 mg/L and the maximum permissible level is 600 mg/L. In Anuradhapura district 34% and 8% of the wells have been reported to be exceeding the maximum desirable and maximum permissible levels of calcium respectively (Perera et al. 2008). Most of the shallow and deep wells in NCP are known to have hardness problem, which is primarily due to calcium. These ions are distributed as carbonate mainly to form dolomite and calcite, the main constitutes of underlying rocks (Dissanayake et al. 1982). According to WRBSL (2013) total hardness of shallow groundwater in Medawachchiya division has a mean value of 287 mg/L Figure 2.10.

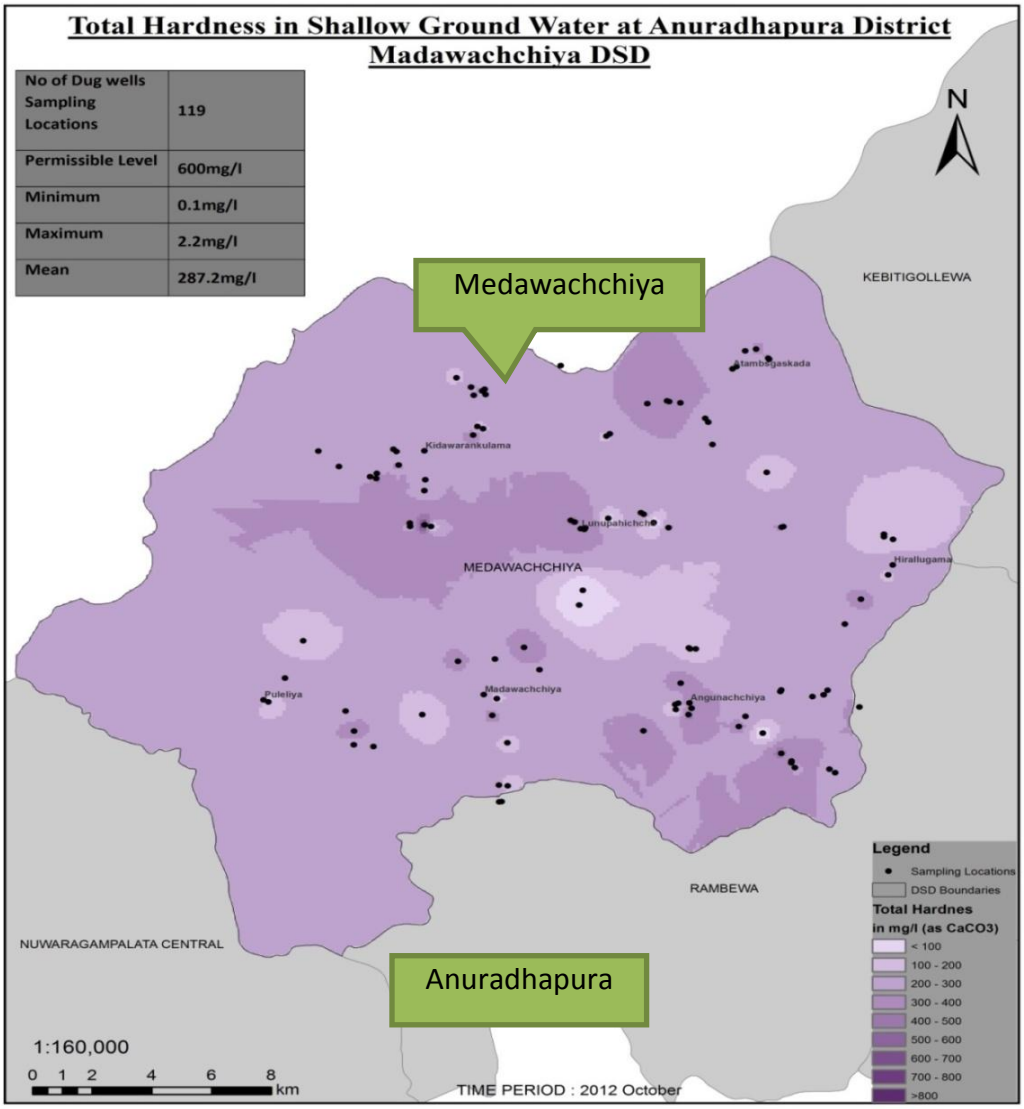


Figure 2.10 Groundwater hardness in the CKD affected area of Medawachchiya in Anuradhapura

(Source: WRBSL 2013)

Both calcium and magnesium are essential elements of the human body and major components of bones and teeth. They also play a role in the decrease of neuromuscular excitability, myocardial system, heart, muscle contractility and blood coagulability (Dissanayake 2008). Magnesium is also a cofactor and activator of more than 300 enzymatic reactions. Magnesium deficiency is linked with hypertension, cardiac arrhythmia and myocardial infraction. As such magnesium in water has an inverse relation with cardiovascular mortality but there is no relation explained in literature between magnesium and CKD (Rylander 1996).

2.5 Heavy metal pollution in NCP

Due to the controversy over the CKD causing factors in NCP, heavy metal pollutants in water and soils have been investigated by some researchers. According to Bandara et al. (2008) the dissolved cadmium in water from five reservoirs supplying irrigation to CKD affected areas are in the range from 0.03 to 0.06 mg/L (WHO standard of Cd^{2+}in drinking water: 0.005 mg/L) and 1.78 to 2.45 mg/kg in sediments. They have suspected Triple Super Phosphate fertilizer (TSP) contaminated with cadmium applied in rice farming to cause CKD. However in a later research by Chandrajith et al. (2010) has shown that water from the same reservoirs contain much lower levels of cadmium concentrations (0.0029 - 0.0089 mg/L). Further investigation revealed that cadmium levels in drinking water of CKD patients are on average 0.003 mg/L (Wasana et al. 2012). Also according to WHO (2012) cadmium concentrations had been at normal levels in sampled wells, tubewells, irrigation canals, pipe-borne supplies, reservoirs and natural springs in CKD endemic and non-endemic areas in Sri Lanka. However cadmium in surface soils of CKD endemic areas has been 1.163 mg/kg and in non-CKD endemic areas 0.493 mg/kg. Also cadmium in urine and nails of CKD patients had been significantly higher compared to non-patients and controls, where cadmium in urine of CKD patients' had been a mean value of 1.039 mg/kg compared to a mean of 0.646 mg/kg in non-patients and 0.345 mg/kg in controls. Cadmium concentrations in CKD patients' nails have been 0.017 mg/kg while 0.009 mg/kg in controls. Same study has revealed that cadmium levels in rice in both CKD endemic and non-endemic areas to be less than the Codex Alimentarius Commission allowable limit. According to FAO (2011) maximum levels of cadmium permitted by the Codex Alimentarius for vegetables is 0.2 mg/kg. The maximum concentration of cadmium had been higher in Lotus roots and tobacco in the CKD endemic areas with mean values of 0.413 and 0.351 mg/kg respectively, and those from CKD non-endemic areas with mean values of 0.02 mg/kg and 0.316 mg/kg, respectively. Maximum cadmium concentration in fish in CKD endemic areas had been 0.06 mg/kg exceeding European maximum limit of 0.05 mg/kg, whereas in the non-endemic areas a lower value of 0.033 mg/kg was obtained (WHO 2012).

Arsenic and mercury which could get added to soil as an impurity in fertilizer and agrochemicals had been suspected to cause CKD in NCP (Fernando 2011). In the CKD

endemic subdivision of Padavi-Siripura in Anuradhapura, arsenic content in groundwater has been found to be in the range of 0.021 to 0.1 mg/L (Fonseka et al. 2012). It is to be noted that WHO permissible level of arsenic is 0.01 mg/L. In contrast another study has shown arsenic concentration in groundwater in CKD endemic areas to be on an average 0.0003 mg/L with the highest value being 0.00081 mg/L, which are well below WHO permissible level (Kawakami et al. 2012). The study by WRBSL (2013) has found arsenic in 76 samples within a range of 0.005-0.01 mg/L out of 128 samples analysed from shallow dug wells and tubewells in CKD endemic area of Medawachchiya (Figure 2.11).

Lead in vegetables of the endemic areas have shown higher concentrations with a mean of 0.476 mg/kg which is much higher than the maximum level permitted by the Commission of European Communities (0.1 mg/kg) (WHO 2012). Lead excretion in the urine of CKD patients to be with a mean of 0.0011 mg/L, having no significant difference with non-patients having a mean of 0.001 mg/L (WHO 2012).

Aluminium has also been suspected to influence CKD in NCP due to the reason that aluminium utensils are cheaply available in rural areas of Sri Lanka which are used by people for cooking, storing and carrying water. CKD had been attributed due to reactivity between aluminium and fluoride in acidic media according to Herath et al. (2005) and Ileperuma (2012). These authors have explained that aluminium release was higher in the presence of fluoride. Aluminium release had been 1.2 mg/L in 6 mg/L fluoride solution; 18 mg/L without fluoride in acidic medium after adding tamarind at pH of 3.02; and aluminium release had been 29 mg/L in 6 mg/L fluoride solution in acidic medium at pH of 3.02 made by adding tamarind. They have explained aluminium-fluoride complexes to play a significant role in causing CKD which can move across phospholipid membranes to release fluoride ions inside the kidney cells.

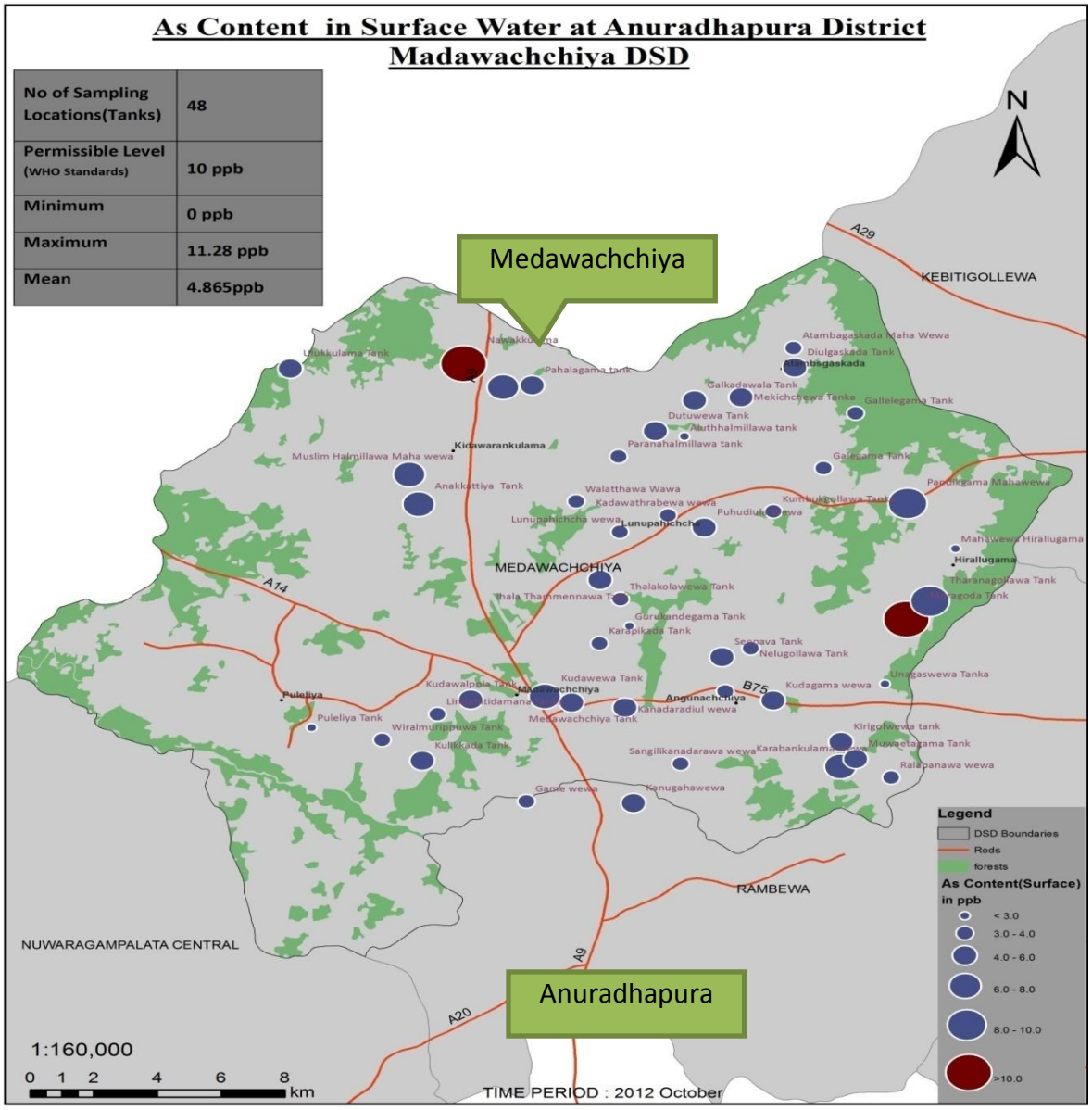


Figure 2.11 Arsenic contents in the surface waters of high prevalence Medawachchiya area (Source: WRBSL 2013)

Some popular cooking ingredients used in Sri Lanka are tamarind, vinegar, tomato and lime juice, are all acidic. In acidic media, aluminium release is found to be higher to combine with fluoride ions to form aluminium-fluoride. A number of programs have been carried out to aware people in the affected areas regarding the dangers of using traditional aluminium utensils. In 2010 a personal visit to the houses of the CKD endemic NCP, revealed that people have given up using aluminium utensils due to awareness of the potential risks. In a recent study by Wasana et al. (2012) drinking water samples collected from CKD endemic subdivisions of Anuradhapura (e.g. Padaviya, Kebithigollewa and Medawachchiya) have

shown average aluminium contents of 0.016, 0.056 and 0.062 mg/L respectively, which are below WHO standard (0.2 mg/L). However some other samples collected from CKD low prevalence subdivisions of Anuradhapura and Pulmoddai have shown average aluminium contents of 0.362 and 0.056 mg/L respectively. As such it is opined that CKD prevalence has not been related to aluminium in drinking water.

According to WHO (2012), chromium (Cr) levels in CKD patients' serum have been found to be within normal limits, but heavy metal of strontium (Sr) had been higher than the normal limit with a mean 0.083mg/L. Some of these findings on heavy metal levels in water in CKD endemic area drinking water are shown in Table 2.5. Investigation by Jayawardena et al. (2012) revealed that lead, zinc, copper and nickel levels were below WHO permissible levels in shallow groundwater sources of NCP. According to WHO (2012), Pb content had been high in one sample from a reservoir of CKD endemic area with a mean of 0.012 mg/L but all other samples from wells, tubewells, irrigation canals, pipe-borne supplies and natural springs including those taken from non-endemic areas had been below maximum contaminant level of 0.01 mg/L.

2.6 Other factors of CKD in NCP

Literature suggests high phosphate levels observed in reservoirs in NCP which supply irrigation water to the CKD affected areas (Chandrajith et al. 2010). This has led to eutrophication of reservoirs in NCP. Generally about 40 species of cyanobacteria belonging to 24 genera have been reported from Sri Lankan reservoirs and among them the highest diversity of cyanobacteria has been recorded from the dry zone reservoirs (Perera et al. 2012). Kala Wewa, Nuwara Wewa, Tissa Wewa, Jaya Ganga and Ridiyagama tank in Anuradhapura district which provide drinking and irrigation water to some areas of NCP have shown toxigenic cyanobacterial diversity dominantly *cylindrospermopsis* (Liyanage et al. 2012, Perera et al. 2012). In another study blue green algae species of microcystis and oscillatoria have been found to be predominant in irrigation tanks of Anuradhapura namely Rajanganaya Wewa, Nachchaduwa Wewa, Nuwara Wewa and Tissa Wewa (Nilusha et al. 2012). Cyanobacterial toxins namely microcystin, cylindrospermopsin (CYN) and deoxy-cylindrospermopsin (DCYN) are known to have acute nephrotoxic effects in experimental animals (Shihana et al. 2012, Liyanage et al. 2012). However water from Padaviya reservoir

providing irrigation water to some areas of NCP have shown low levels of DCYN (< 0.05 µg/L) and no CYN or microcystin (Dissanayake 2012).

Acetyl cholinesterase (Ache) has been the most widely used pesticides in Sri Lanka and therefore, exposures to this pesticide and organophosphate have been predicted to cause CKD by Peris et al. (2006). According to WHO (2012) some pesticide residuals detected in the urine of CKD patients were namely 2,4-D (3.5%), pentachlorophenol (1.7%), chlorpyrifos (10.5%), carbaryl (10.5%), naphthalene (10.5%) and glyphosate (3.5%).

Other predictors of CKD in NCP are family history and traditional medicinal treatment (Ayurvedic medicine). Similar situations are known in other countries where uses of certain non-prescription drugs, such as heroin or cocaine, are known to damage the kidneys leading to kidney failure. Snake bites have been another cause of CKD suggested by Wanigasuriya et al. (2007). WHO (2012) has shown snakebites in 121 (16%) CKD patients out of total 775 patients analysed.

2.7 Statistical analysis techniques

Exploratory data analysis (EDA) approach is commonly used to analyse data and to summarize their main characteristics. In this research EDA was applied to find out the water quality differences in the sampling groups using the parameters like mean, maximum, minimum, standard deviation and median. EDA has been used by previous researchers to evaluate water quality accounting for seasonal, spatial and anthropogenic influences (Einax et al. 1998, Vega et al. 1998, Simeonov et al. 2000, 2001, 2002, Marques da Silva & Sacomani 2001, Brodnjak-Voncina et al. 2002, Alberto et al. 2001, Mendiguchia et al. 2004, Singh et al. 2004, 2005, Ouyang 2005, Ouyang et al. 2006, Panda et al. 2006, Kowalkowski et al. 2006, Charkhabi et al. 2006, Sojka et al. 2008).

Further to EDA more complex multivariate statistical analyses were carried out in this research to find out water quality differences in the sampling groups. Commonly used multivariate statistical analysis techniques used in water quality analysis are Cluster Analysis (CA), Factorial Analysis / Principal Component Analysis (FA/PCA) and Discriminant Analysis (DA).

There are many multivariate statistical tools available to assess water quality differences. Among them Factorial analysis is a useful tool to identify inter correlations among variables which has been used in many previous researches to identify major underlying factors contributing to variations in chemical water quality parameters. Also factor analysis has helped to identify groundwater and surface water quality parameters and to identify the major pollutant sources (Wen-Cheng et al. 2011, Singh et al. 2004, Li et al. 2007, Liu et al. 2003, Shrestha & Kazama 2007, Reghunath et al. 2002). For example Liu et al. (2003) have applied Factorial Analysis (FA) to 28 groundwater samples collected from wells in the Coastal Blackfoot disease area of Yun-Lin, Taiwan to interpret statistically significant correlations among 13 hydro chemical parameters. Cluster Analysis (CA), Factorial Analysis/Principal Component Analysis (PCA) and Discriminant Analysis (DA) have been used by Singh et al. (2004) to evaluate water quality of Gomti River (India). They have evaluated 24 parameters of 17,790 observations with those techniques. PCA and CA techniques have also been used by Judite et al. (2012) to evaluate the spatial variations of surface water quality data in Lis River, Portugal. It has evaluated 27 physicochemical and microbiological parameters in six water sampling campaigns at 16 monitoring sites.

Some other water quality studies carried out using multivariate statistical analysis include: Pisuerga river (Spain) by Vega et al. (1998), Ave river (Portugal) by Soares et al. (1999) and Alves et al. (2009), Guadalquivir river (Spain) by Mendiguchía et al. (2004), Contas river basin (Brazil) by Santos et al. (2004), Fuji river basin (Japan) by Shrestha & Kazama (2007), Trancão River (Portugal) by Picado et al. (2008), Jajrood river (Iran) by Razmkhah et al. (2010), Pisuerga river (centre-north of Spain) by Vega et al. (1998), Nethravathi catchment (India) by Reghunath et al. (2002) to name a few.

All these statistical methods have led to classification of water pollutants by grouping them according to their sources. This has led to a better understanding of the water quality of the studied systems.

2.8 Rainwater harvesting (RWH) as a CKD mitigation method

Rainwater harvesting (RWH) is proposed in this research as an alternative to groundwater source in NCP. Rainwater harvesting is convenient because it provides water at the point of

consumption. However rainwater harvesting is not widely practiced in the CKD endemic area due to poor economic status of people in managing RWH systems and insufficient knowledge of required tank capacities. Tank calculations are carried out based on various simulation models which are not available at NCP. Therefore Rainwater tank size calculation was carried out to the proposed areas to estimate the optimum tank sizes. Rainfall data of the past years was the basis for prediction of future rainfall.

Unavailability of suitable catchment surfaces to collect rainwater was also seen as a practical limitation to RWH in NCP. Some of the houses in the area were with asbestos roofs whereas some other houses were with tin and thatched roofs. Depending on the roofing material some of them did not provide a suitable and smooth catchment surface suitable for RWH. The quality of harvested water varies with the roofing material and also the roof area may or may not be sufficient for rainwater quantity to be collected. Therefore, estimation of catchment surfaces was also carried out in this study.

Rainwater harvesting (RWH) in Sri Lanka goes back to 477–495 AD when King Kasyapa built a reservoir cut into a huge rock in the ancient city of Sigiriya to store rainwater (Moonesinghe 2004). Today rainwater harvesting is generally practiced in small scale using any kind of container to capture rain directly from the skies. Other RWH systems existing in Sri Lanka include Ferro cement tanks above and underground using pumpkin shaped tanks (Figure 2.12). Pumpkin tanks are on an average capacity of 5 m^3 (Moonesinghe 2004). Disadvantages of pumpkin tanks are un-manageable size and high construction cost at household level. Personal experience indicated that sufficient catchment surface is not available to fill these tanks which make them go empty during dry periods. Approximately 14,000 smaller RWH tanks of average 225-350 L capacity are functioning in Sri Lanka according to Moonesinghe (2004). The under capacity of these tanks indicate that insufficient water available for family drinking requirements especially in dry periods.

Figure 2.12 Pumpkin tanks in Sri Lanka

(Source: Rainwaterharvesting.org 2012, Moonesinghe 2004)

2.8.1 Rainwater pollution

Rainwater may be polluted from different sources. Major rainwater pollutants are *E. coli* which results from faecal material, dead animals and insects either in gutters or in the tanks. The first flush of rainwater is known to carry higher than average amounts of dust, bird and animal droppings, leaves and other debris from catchment to add faecal coliform into water (Yaziz et al. 1989, Aladenola & Adeboye 2010, Coombes et al. 2007). As such there are instances with faecal coliform exceeding the specified limit in rainwater (Zhu et al. 2004). Yaziz et al. (1989) have shown the water quality to improve once the first 5 L of water is diverted from the roof guttering. According to TWDB (2005) first flush diversion of at least 10 gallons per 1,000 square feet are recommended.

E. coli levels have been found to vary with the type of roof material. For example *E. coli* levels in Galvanised Iron (GI) roofs have been found to be less than other roofs due to heating which kills *E. coli* (Vasudevan et al. 2001, Aladenola & Adeboye 2010). In Sri Lanka *E. coli* levels have been below the WHO permissible level of less than 10 in 100 mL of water in 55% of the rainwater tanks (Ariyananda 2003).

Filtration and disinfection are also recommended before using rainwater for domestic use (Aladenola & Adeboye 2010). Disinfection is used to remove any microorganisms whereas filtration removes debris and any foreign particles in water. Charcoal and gravel filters have been tested to be effective in filtering rainwater in Sri Lanka after the first flush (Ariyabandu 1999).

Disinfection by chlorination (using sodium hypochlorite bleach) is a commonly used effective method against harmful bacteria and many viruses. It also removes odours from rainwater by oxidising the responsible chemicals. A chlorine residual of at least 0.2 mg/L is recommended by TWDB (2005) for effective removal of harmful microorganisms. However effectiveness of chlorine is short lived as it will only act on water at the time of dosing and not to newly added water after chlorination requiring repeated application. Solar light and boiling are alternative methods recommended for disinfection. Solar thermal water disinfection is another method which uses heat from the sun to heat water to 70-100°C for a short period of time. Another method is using high energy ultraviolet (UV) radiation from the sun to kill pathogens in water. UV irradiation has advantages of relatively low maintenance costs and non-involvement of chemicals. It is specially recommended for people with lower immune responses, such as very young or very old, cancer patients and people with diabetes.

Rainwater storage tanks are to be kept covered to prevent mosquito entry as these can provide excellent habitats for breeding. These also act as breeding sites for vector dengue virus in tropical and subtropical areas which are also found in Sri Lanka. Treatments to kill mosquito larvae present in rainwater involve adding medicinal or liquid paraffin or kerosene with a recommended dose of 5 mL (or one teaspoon) kerosene for a 1000 L tank and up to 15 mL (or 3 teaspoons) for a 10,000 L tank (TWDB 2005). Paraffin is also recommended in the same report with a double dose.

Sediments and slimes at the bottom of rainwater tanks or pipes may cause water stagnation leading to undesirable taste and odour. As such recommended measures are to be kept roof catchments clear of overhanging trees and vegetation. Other measures include applying leaf screens and leaf guards to cover inlets to tanks; mesh screens for trapping debris both before and after the storage (TWDB 2005). Another option proposed by Ashworth (2005) to

keep rainwater tanks clean is to use two or more tanks instead of one of the same capacity to remove pathogens that die-off. Tanks are also to be protected from light to control the growth of algae.

Apart from point source pollution, there can be non-point urban pollution caused by atmospheric conditions and other pollutants (Chang et al. 2004, Sazakli et al. 2007, Simmons et al. 2001 and Hou et al. 2012). For example nitrates and sulphates are added to rainwater due to air pollution. However Zhu et al. (2004) have shown both the first flush and harvested water from roof-yard catchment systems to be safe from organic and inorganic compounds to match WHO standards. In the research area of NCP there are no large-scale industries and it is free of urban pollution. Therefore atmospheric pollution is not foreseen as an obstacle to RWH to this area.

2.8.2 Rainwater tank estimation methods

There are two basic approaches for determining rainwater tank sizes, namely Demand approach and Supply approach. Demand approach is a simple method which assumes there is sufficient rainfall and catchment area to meet demand throughout the year (Rees 1999). The Supply approach focuses on the supply-side of rainfall which counts the water supply by rainfall as well as water demand or consumption over time. Also it compares the pattern of rainfall to usage over the course of a year, balancing demand and supply in water shortage months, water surplus months and equal demand and supply months (Jothiprakash & Sathe 2009). Mass curve method based on Supply approach is known to give better result when there is limited rainfall (Ngigi 1999). Therefore, this method was applied for tank size estimation in NCP.

2.9 Fluoride removal techniques from water

Due to fluoride toxicity to humans, extensive research has been done on removal of excess fluoride from water based on coagulation-precipitation, ion-exchange, membrane separation, biodegradation and adsorption principles. There are certain advantages and disadvantages of those principles which are summarised in Table 2.6. In fluoride rich rural areas in Sri Lanka central treatment plants for de-fluoridation are lacking as they are un-affordable to the community. Chemical processes of de-fluoridation have drawbacks due to

complex design leading to high operational and maintenance costs. Change of filters, pH control and sludge removal are some drawbacks of these procedures, which act as limiting factors when operated at domestic level.

Cheaper adsorption processes experimented in Sri Lanka using natural adsorbent material include filters made of serpentine and kaolinite for de-fluoridation (Dissanayake 1991). However, currently none of these processes function at domestic levels due to given drawbacks. In 2013 a non-governmental organization called “Jalani” has implemented 14 reverse osmosis plants in NCP each with a processing capacity of 100 L/hour. Maintenance costs are reported as a limitation for them too. Therefore the aim of this research was to develop a simple and low-cost fluoride removal process using available natural resources that can be applicable to the CKD endemic areas of NCP.

Ion-exchange methods include use of anion-exchange resin containing quaternary ammonium functional groups (Guo & Reardon 2012, Viswanathan & Meenakshi 2008). This method is found to be efficient for 90–95% fluoride removal; however efficiency reduces in the presence of ions like sulphate, carbonate, phosphate and alkalinity. Regeneration of resin is also a problem because it leads to fluoride rich waste. This technique is also expensive because of the cost of resin. Also pre-treatment is required to maintain pH and regeneration and waste disposal.

Coagulation-precipitation using alum and lime is carried out to remove fluoride from wastewater with typically greater than 10 mg/L concentrations (Sollo et al. 1978, Sujana et al. 1998). It is a simple and economical method which removes 18–33% of fluoride as a precipitate. It converts 67–82% of ionic fluoride into soluble aluminium fluoride complex which is toxic (Meenakshi & Maheshwari 2006). The disadvantage of this method arises due to residual aluminium in treated water which is known to be dangerous when in excess of 0.2 mg/L causing structural and biochemical changes in the body affecting musculoskeletal, respiratory, cardiovascular, endocrine and reproductive systems (Meenakshi & Maheshwari 2006, Nayak 2002). Also regular analysis of feed and treated water is a requirement of this method to calculate the correct dose of chemicals to be added leading to high maintenance cost. Large space is required for drying the sludge. De-fluoridation capacity by this method is

also found to be low with treated water having fluoride levels above WHO limit (Tavallali & Daneshyar 2012).

Electro dialysis is another ion-exchange method carried out with or without pre-treatment (Amor et al. 2001). Electro dialysis without pre-treatment has been suggested to be preferable because it is technically simple and chemical free. Both these methods, with or without pre-treatment, are found to meet drinking water standard of fluoride ions, however, a limitation of the method is the unconstrained removal of other essential minerals required for humans body.

Membrane processes described in literature include reverse osmosis (Simons 1993), Donnan dialysis (Kir & Alkan 2006) and nano-filtration (Tahaikt et al. 2008). Membrane processes are found to be highly effective for fluoride removal up to 98%. However membrane processes are costly and its efficiency is governed by factors, such as raw water characteristics, pressure, temperature and regular monitoring and maintenance. Also these processes are found to remove all the ions present in water essential for body. Therefore, re-mineralization is necessary after treatment. Brine formation is also described as a problem in membrane processes.

Adsorption is another method to remove fluoride from water. Natural, synthetic, and biomass materials are generally used as adsorbents in this method. Adsorption is known as a viable method for removal of fluoride because it is easy to operate, cost effective and applicable at low concentrations. Some of the low-cost adsorbents used for the removal of fluoride include calcite, activated saw dust, activated coconut shell carbon, activated fly ash, activated alumina, groundnut shell, rice husk, magnesia, tri calcium phosphate, bone charcoal, zeolite and hydrated cement, red mud, alum sludge, chitosan beads, etc. A list of low cost absorbents given in Table 2.7. Adsorption is a better technique than others based on initial cost requirement, flexibility and simplicity in design, operation and maintenance.

Plant materials are also found to act as absorbent material to remove fluoride. Some of the plant materials investigated by Harikumar et al. (2012) are Vetiver root (*Vetiveria zizanioides*, 80%), Tamarind seed (*Tamarindus indica*, 75%), Clove (*Eugenia carryophyllata*, 70%), Neem (*Azadirachta indica* 52%), Acacia (*Acacia catechu wild*, 47%), Nutmeg (*Myristica*

fragarns, 45%), and Coffee husk (*Coffea arabica*, 38%). However removal capacities of most natural absorbents are found to decrease with decreasing fluoride concentrations (Majima & Takatsuki 1987) while some of the adsorbents do not remove fluoride levels below 2 mg/L (Wang & Reardon 2001). According to Tripathy et al. (2006), only a few adsorbents are known to reduce the concentrations of fluoride down to or below the 1.0–1.5 mg/L to reach WHO standard while adsorption process with some other natural adsorbents are known to be pH dependent requiring solutions to be acidic (pH < 3) which does not favour the quality of drinking water (Mckee & Johnston 1999, Puka 2004, Mayadevi 1996, Chaturvedi et al. 1988).

In this research three types of plant material were tested for fluoride adsorption namely curry leaves, turmeric and ginger powder. They were chosen on the criteria of cheaply available and naturally growing in the CKD endemic areas. Turmeric is a member of the ginger family (*Zingiberaceae*). Turmeric powder is a deep yellow spice made from dried rhizomes of turmeric (Figure 2.13) which is traditionally used in Sri Lanka to purify water and as a natural antiseptic. Turmeric is also named as Circumin 1, Circumine, Indian saffron and Turmeric yellow. It is commonly used as a food colorant and therefore also given names as natural yellow 3 (E100) and CL 75300. Generally turmeric contains anti-oxidant, anti-dyspepsia, anti-platelet, anti-viral and anti-fungal effects. They also have anti-inflammatory and anti-bacterial effects. Turmeric has been found to cure some major diseases like Alzheimer, Arthritis, Cancer and Diabetes (Yang et al. 2005, Ono et al. 2004, Lim et al. 2001, Molnar & Garai 2005, Funk et al. 2006, Zheng et al. 2004).

Table 2.6 List of studies on different fluoride removal techniques

Method	References	Advantages	Disadvantages
Coagulation-precipitation using alum and lime	Sollo et al. 1978, Sujana et al. 1998	Effective to remove high fluoride amounts more than 10 mg/L	Low fluoride adsorption capacity with 18-33% fluoride removal. Forms aluminium fluoride which is a toxic soluble complex. High maintenance cost.
Ion-exchange using resin	Guo & Reardon 2012	High fluoride adsorption capacity with 90-95% fluoride removal	Expensive due to cost of resin. Water becomes acidic after treatment. Require frequent regeneration of resin.
Electrodialysis	Amor et al. 2001	Effective	Expensive. Require cleaning of membranes. Scaling and fouling.
Reverse osmosis	Simons 1993	High fluoride removal capacity about 98%	Membrane is expensive. Needs regular maintenance due to fouling of membranes. Removes all ions present in water, needs re-mineralization after treatment. Water becomes acidic after treatment.
Donnan dialysis	Kir & Alkan 2006	Economical	Process is pH dependent.
Nano-filtration	Tahaikt et al. 2008	Effective	The process is yet to be developed to be applied practically.
Sedimentation with calcium and aluminium salts	Aldaco et al. 2005	Suitable for fluoride-rich industrial wastewater	Process generates large amounts of fluoride-containing sludge. Sludge treatment and disposal is a problem with increased costs. Reduces fluoride concentrations to about 2 mg/L which is above WHO limits.

Table 2.7 Low cost adsorption methods

Method	References	Advantages	Disadvantages
Activated alumina	Ghorai & Pant 2005, Tripathy et al. 2006	High fluoride removal capacity about 90% Cost effective	The process is pH dependent, requiring solution to be pH 5.0-6.0. High concentration of total dissolved salts (TDS) which causes fouling of alumina bed. Presence of other ions of sulphate, phosphate or carbonate results in ionic competition. Disposal of fluoride laden sludge and concentrate regeneration is a problem.
Powdered activated carbon	Mckee & Johnston 1999	Cheap material	The process is pH dependent requiring solutions to be acidic (pH < 3).
Clay	Puka 2004.	Cheap material	Adsorption is concentration dependent. The process is pH dependent requiring solutions to be acidic (pH < 3).
Red mud	Mohapatra et al. 2009, Gandhi et al. (2012), Tor et al. 2009	High fluoride removal capacity of 71%	Minimum fluoride adsorption to be 3.4 mg/L. Red mud is too alkaline (pH 10-12) for use.
China clay	Mayadevi 1996, Chaturvedi et al. 1988	Cheap material	The process is pH dependent requiring solutions to be acidic (pH < 3).
Concrete	Huang et al. 1999, Gandhi et al. 2012	Fluoride removal capacity about 38%	Minimum fluoride adsorption to be 5.6 mg/L.

Table 2.7 Low cost adsorption methods (*Contd.*)

Method	References	Advantages	Disadvantages
Lignite, Kaolinite clay, Nirmali seeds	Srimurali et al. 1998	Not given	Low fluoride removal capacity of 6 to 8%.
Ragi seed powder	Gandhi et al. 2012	Removal of fluoride about 65%	Minimum fluoride adsorption to be 4.2 mg/L.
Horse gram seed powder	Gandhi et al. 2012	High fluoride removal capacity about 75%	Minimum fluoride adsorption to be 3 mg/L.
Orange peel powder	Gandhi et al. 2012	High fluoride removal capacity about 79%	Minimum fluoride adsorption to be 2.5 mg/L.
Chalk powder	Gandhi et al. 2012	High fluoride removal capacity about 86%	Minimum fluoride adsorption to be 1.6 mg/L.
Pineapple peel powder	Gandhi et al. 2012	High Fluoride removal capacity about 86%	Minimum fluoride adsorption to be. 1.6 mg/L.
Multhani mattired mud	Gandhi et al. 2012	Fluoride removal capacity about 56%	Minimum fluoride adsorption to be. 5.26 mg/L.
Fly ash	Chaturvedi 1990	Not given	Low fluoride removal capacity. The process is pH dependent requiring solutions to be acidic.
Chitin or chitosan based materials	Viswanathan & Meenakshi 2008	Not given	Low fluoride removal capacity.

Figure 2.13 Turmeric tubers and turmeric powder
(Source: TMV 2013)

2.10 Summary

In literature review CKD situation in NCP of Sri Lanka is discussed. Probable CKD causing factors are identified in relation to specific geographical characteristics in the problem areas. Fluoride pollution in the CKD endemic areas is identified as a research gap which needs to be investigated further. The statistical analysis techniques which were used to analyse data are also introduced in this chapter. Rainwater harvesting is discussed as mitigation measure as an alternative drinking water source. Mass curve method was applied for calculation of rainwater tank sizes as discussed in this chapter. Lack of suitable surface as catchment to collect rainwater is identified as limitation to rainwater harvesting in the CKD endemic areas of NCP. As such the research is aimed to estimate the minimum catchment surface required to collect rainwater for filling tanks depending on average rainfall and tank capacity. Finally fluoride adsorption using available natural adsorbents were investigated as a CKD mitigation technique.

3 METHODOLOGY – I : STATISTICAL ANALYSIS TO IDENTIFY CKD CAUSES

This chapter describes the study area of NCP in Sri Lanka. It also explains the sample collection program, sample locations and number of samples collected. The selection of statistical analysis tools and procedures appropriate for the data analysis are also described. Statistical analysis tools used are namely Box plots, Univariate Analysis of Variance (ANOVA) with Dunnett's T3 post-hoc test, Kruskal-Wallis (KW) test with Mann-Whitney's post-hoc test, Factorial Analysis (FA) and Discriminant Analysis (DA).

3.1 Study area and sample collection program

Sri Lanka is a subtropical island in the Indian Ocean. It is located towards south of the Indian sub-continent between latitudes of 5° 55' and 9° 55' north and longitudes 79° 42' and 81° 52' east. The total area of Sri Lanka is 65,610 sq. km. It has a population of 21.5 million with a growth rate of 0.9% according to census of 2001. It is divided into nine major administrative units which are called provinces (Figure 3.1). North Central Province (NCP) is the largest province covering 15% of the total land area and it has a total population of 1.1 million which is approximately 5.5% of the total population of the country. NCP lies in the dry zone of Sri Lanka receiving an average annual rainfall of 1500-2000 mm and a mean annual temperature of 30°C (DMSL 2012). NCP is further divided as Polonnaruwa and Anuradhapura districts. Anuradhapura is the larger district with a land area of 6,664 sq. km and Polonnaruwa district has a land area of 3,077 sq. km. According to census of 2001, Anuradhapura district has a total population of 745,693 (112 persons per sq. km) and Polonnaruwa district has a total population of 359,000 (117 persons per sq. km).

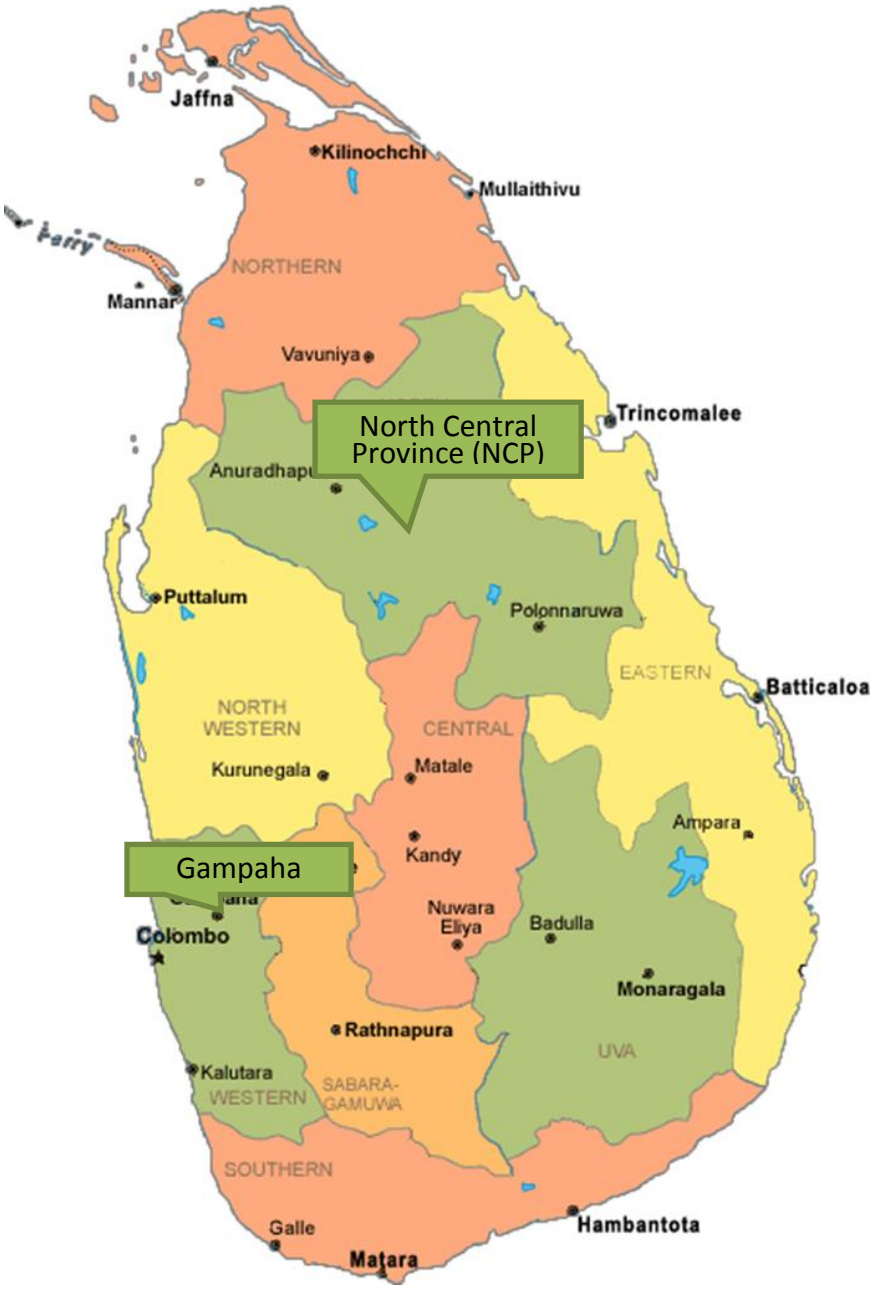


Figure 3.1 The map showing the provinces in Sri Lanka

(Source: DAPH 2013)

Sample locations were identified based on the abundance of CKD patients. As such Anuradhapura and Polonnaruwa districts were the sampling districts which were the highest CKD patient districts in the country. The sampling sub divisions were Medawachchiya and Padaviya village divisions in Anuradhapura district and Medirigiriya village division in Polonnaruwa district (sample locations are shown in Figure 3.2).

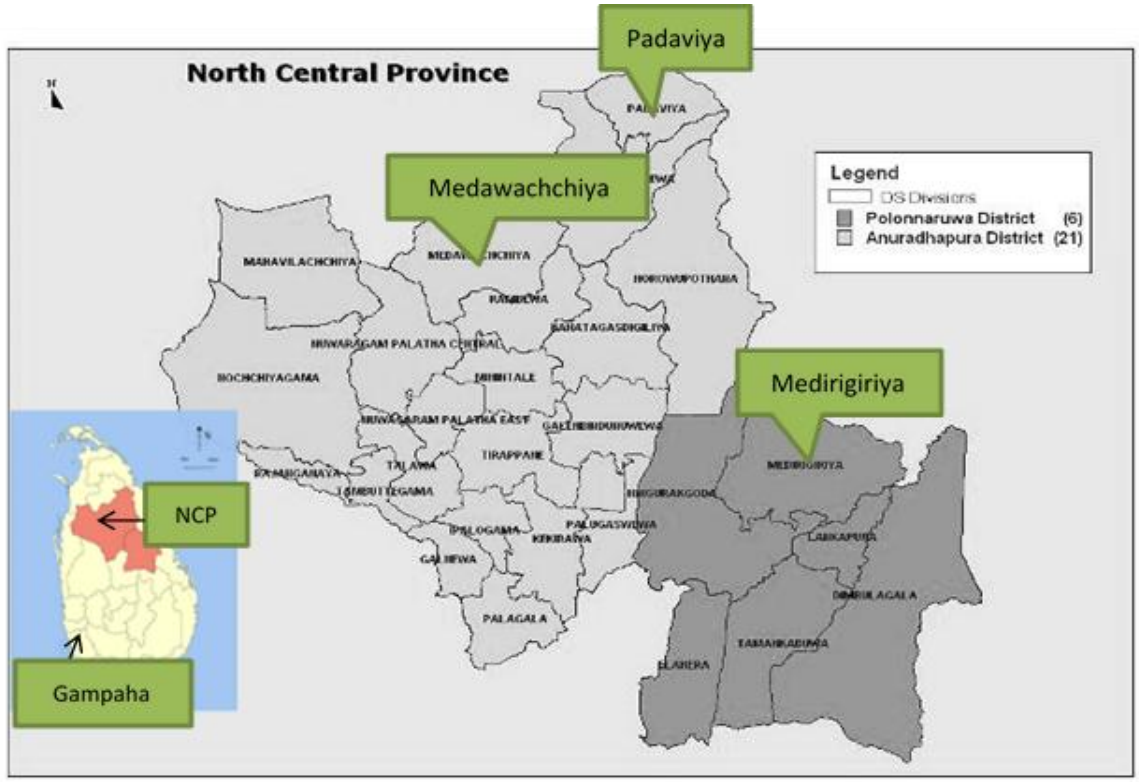


Figure 3.2 Sample collection areas in Anuradhapura and Polonnaruwa district
(Source: DAPH 2013)

Gampaha district located far south-east from NCP, was selected as the control area, free from CKD. The aquifer of this area contains undifferentiated metasediments that differs in composition from NCP (Dissanayake 1991). Gampaha is in the wet zone receiving an average annual rainfall of 2000-2500 mm/year and a mean annual temperature of 27°C (DMSL 2012). Wet zone of Sri Lanka has been identified as a low fluoride area by Dissanayake (1991). As such the main difference between the CKD endemic area and control area is that CKD endemic area is underlain by fluoride bearing minerals whereas control area of Gampaha is not.

Patient and non-patient samples were grouped as Anuradhapura patients (ANU-P) and Anuradhapura non-patients (ANU-NP). There were 102 samples from ANU-P and 60 samples from ANU-NP. These samples were collected from both Padaviya and Medawachchiya subdivisions. Polonnaruwa patients (POL-P) and Polonnaruwa non-patients (POL-NP) samples were collected from Medirigiriya which consisted of 90 POL-P samples and 60 POL-NP samples. Control samples collected from Gampaha were named as GAM-C which

consisted of 20 samples. All these sampling groups which were used in primary data analysis are shown in Figure 3.3 along with their number of samples in each group.

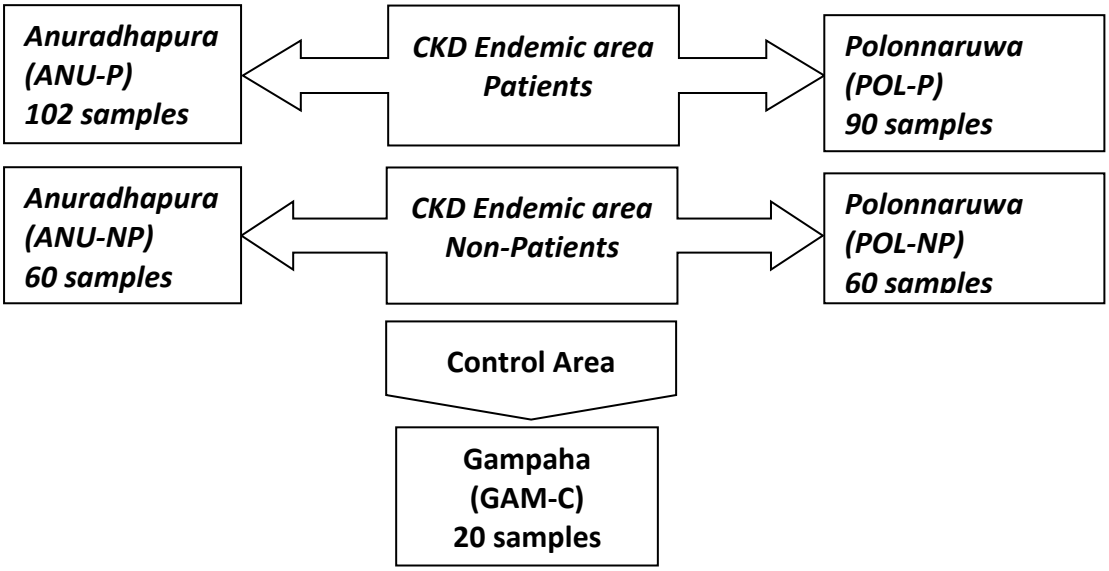


Figure 3.3 Sampling groups with number of samples in each group

In addition to this a secondary data set (.

Table 3.1) collected by Chandrajith et al. (2010) was also analysed in this research. Those samples have been collected from CKD endemic areas of Girandurukotte (47), Nikawewa (52), Medawachchiya (11) and Padaviya (35) and CKD non-endemic areas of Huruluwewa (30) and Wellawaya (8). The total number of secondary data was 183. In order to get a clear picture, sampling locations of primary and secondary data are also shown in Figure 3.4.

Table 3.1 Secondary data collected by Chandrajith et al. (2010)

Area	CKD prevalence	Number of samples
Girandurukotte	Endemic	47
Nikawewa	Endemic	52
Huruluwewa	Non- Endemic	30
Medawachchiya	Endemic	11
Padaviya	Endemic	35
Wellawaya	Non -Endemic	8
Total samples		183

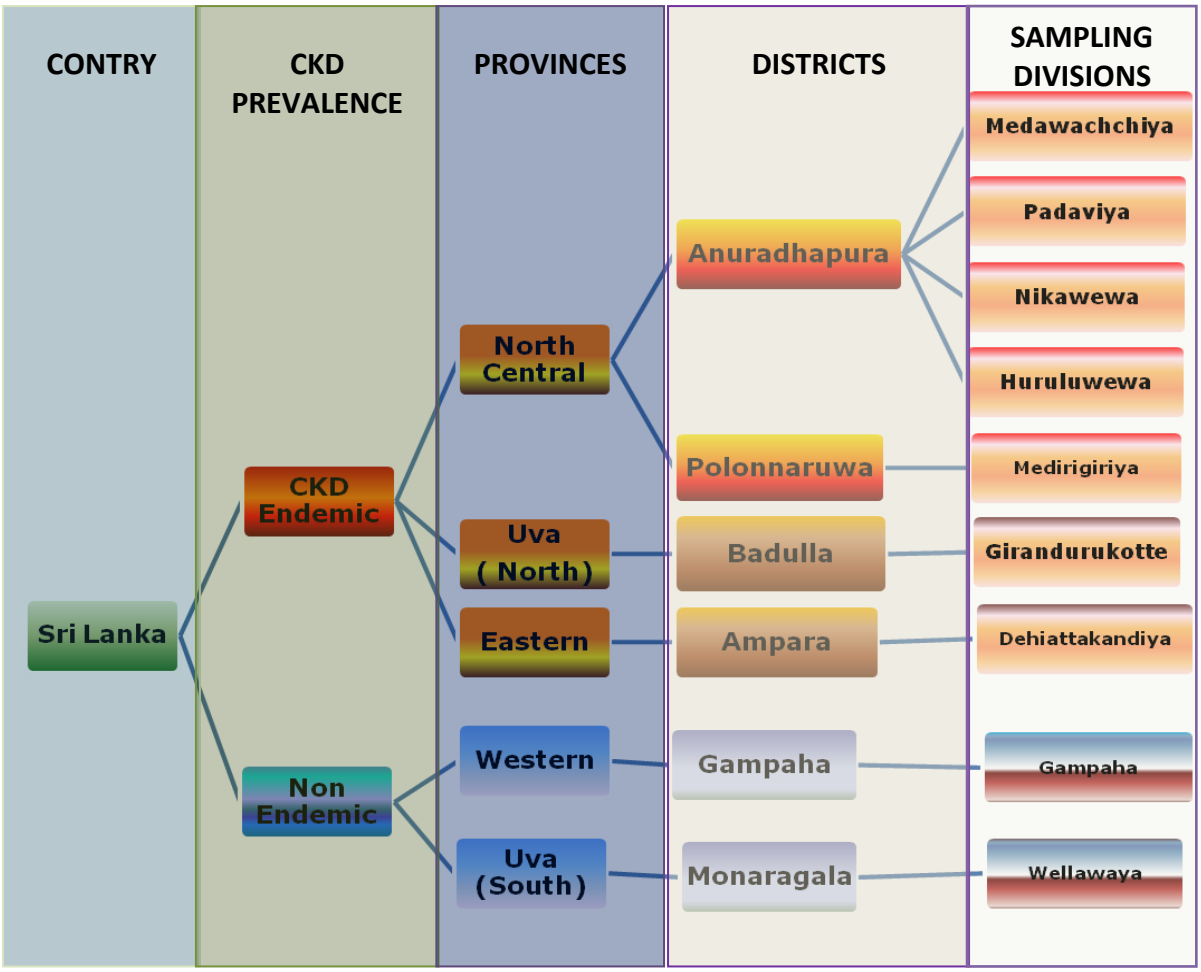


Figure 3.4 Sampling locations of primary and secondary data collected

Field investigations in the CKD endemic areas showed that shallow hand dug wells of average 5-10 m depths being used to extract water for drinking and household purposes. Water from deep wells (10-30 m) was not used for drinking due to undesirable taste and hardness associated with high carbonate content. Therefore water samples were collected from hand dug wells in the CKD endemic locations for both patients and non-patients. CKD patient locations (addresses) were obtained from CKD patient lists in district clinical registrations. Random samples were collected from both CKD patient and non-patient drinking water wells. Those wells chosen for sampling have been used for drinking by CKD patients or non-patients for more than 10 years as the only drinking water source. Non-patient water wells were confirmed that none of the users in the family have had any history of CKD. In that effort, absence of CKD patients in the family was reconfirmed by carrying out a field urine test on persistent albuminuria (Albumin-Creatinine Ratio ≥ 30 mg/g urine) by the longest water user in that family/household. Sample collection period was

December 2010 to August 2011. The sample collection team consisted of the main researcher (candidate), a research partner and a medical doctor.

Fluoride (F^-), calcium (Ca^{2+}), sodium (Na^+) and magnesium (Mg^+) are the main ions involved in groundwater chemistry common to CKD endemic areas of Sri Lanka (Young et al. 2011). Totally the chemical parameters analysed were chloride (Cl^-), fluoride (F^-), nitrate (NO^{3-}), phosphate (PO_4^{3-}), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), cadmium (Cd^{2+}) and arsenic (As^{3-}). Cd^{2+} and As^{3-} were also analysed in patient water samples due to the assumptions in the literature that they could be possible factors in causing CKD. Water samples were collected in PVC bottles. Sample testing was carried out in a commercially accredited laboratory named SGS Laboratories (Pvt) Ltd in the capital of Colombo. Test protocols used by the lab include: 3120 APHA 21st ED for arsenic, cadmium, sodium, magnesium and calcium; 4500 APHA 21st ED for fluoride, chloride and total phosphate; 4500 APHA 21st ED for nitrate. Preservatives of HNO_3 and H_2SO_4 were added according to the above standard procedures before they were transported to lab. Temperature and pH values of each sample were tested in the field (using pH meter: model ATPH-6).

3.2 Selection of statistical analysis tools and procedures

According to literature there were no anthropogenic polluting agents found in the endemic area, and 85% of the affected community obtain water from shallow wells. As such the assumption made in developing the methodology of research was that CKD in NCP was originating from drinking water sources.

With reference to fluoride levels in drinking water, maximum permissible level recommended by WHO (1993) is 1.5 mg/L which is the national standard followed in Sri Lanka. However there is a maximum desirable level of 0.6 mg/L recommended for tropical countries (Perera 2008). In the research results, initially fluoride levels of the specific sampling groups were compared with the WHO permissible level.

Although average values are good enough to have a general idea, a drawback of considering the average value of a sampling group is that it does not give the exact value of each sample location (drinking water well). However individual values of each sampling location was assumed to be significant requiring discrete investigation in this study due to dispersion of

CKD patients and non-patients in the area who consumed water from their individual wells. For example certain households consuming water from wells were affected by CKD whereas a neighbouring household consuming water from a well approximately 100 m away were not affected. In worse situations there were instances where more than one person in a household was affected by CKD while there were no patients in a neighbouring household.

Taking median value of a sampling group is another option as it gives the middle value of the sample population. Box plots were created to show the median values of each water parameter in the selected sampling groups. The median values of each parameter were compared with the WHO standards and distributions of data in inter-quartile ranges were interpreted.

According to literature, fluoride levels in water are related to many other parameters and vary with underlying geology. Therefore other parameters in water related to fluoride were also investigated in this research and compared between patients and non-patients using primary and secondary data.

During the initial sample collection campaign heavy rain occurred unexpectedly restricted the sample collection at a single period of time. Dilution of groundwater wells could occur to show lower values than expected. Therefore some sample data gave values in the rainy period while other values were based on non-rainy period. However in the analysis each parameter was compared among the sampling groups to avoid the seasonal effects as all the sampling groups were equally affected by the dilution effect in that rainy period. As such selected parameters were compared between two or more sampling groups in this research.

The basic statistical procedure followed for comparison among the sampling groups is shown in Figure 3.5. Accordingly simple comparison tests are applied when there are two groups, whereas complex group comparisons are carried out if more than two groups are compared. Both simple and complex group comparisons are divided into parametric and non-parametric tests. Basic requirements for parametric tests are that data requires to be normally distributed and the different data groupings should have the same variance or standard deviation. On the other hand non-parametric tests do not require the data to be

normally distributed and different data groupings may not have the same variance or standard deviation. Therefore non-parametric tests are known to be less restrictive but have less statistical power than parametric tests. However, if the data are not normally distributed, non-parametric tests are recommended as the parametric tests are known to lose any advantage if inappropriately applied.

Independent tests are carried out when the data cannot be related to each other. For example independent tests are used if the samples cannot be collected to represent similar conditions due to physical separation in sampling locations. However independent tests were not applicable in this research according to research assumptions.

A simple comparison test for independent as well as dependent samples is Student's T-test which is a parametric test. Student's T-test is carried out to find within group variation. Paired tests are carried out when variables other than the variable being tested between two groups are kept constant. Paired test are known to be more efficient than independent tests and are carried out on the assumption that the uncontrolled factors basically influence both sets of data observations equally (Berthouex and Brown 1994). Paired tests carried out in this analysis were Dunnett's T3 and Mann-Whitney's post-hoc tests.

As patient and non-patient water samples were in close vicinity with each other, average values and common ranges of parameters in the five sampling groups compared were expected to be similar. In such situation those values which showed marginal but significant differences especially in patient samples, had to be identified effectively. Therefore, one comparison test was not deemed adequate in this research but a number of comparison tests that lead to the final conclusion to identify the differences/non-differences between the groups confidently needed to be applied. Hence, both paired and complex group comparison tests were applied to analyse the differences in parameters. Complex group comparison tests used in the research analysis were ANOVA and Kruskal-Wallis (KW) tests. All these tests are further described later in this chapter.

Statistical power is another important consideration given in statistical analysis. Under that there are two types of errors which influence decision making, namely Type 1 and Type 2 errors. Type 1 error (also known as "α "error) indicates a false positive. An example given by

Burton & Pitt (2001) is the conclusion that tested water was adversely contaminated, when it was actually clean. In water research the most commonly used value is $\alpha < 0.05$, which means accepting a 5% risk of having a Type 1 error. When accepting a 5% risk of Type 1 error the confidence of not having a false positive is $(1 - \alpha)$ or $(1 - 5\%)$ which is also called 95% confidence level. This was the confidence level used in the analysis. Type 2 error in statistical calculation (also known as "β" error) indicates a false negative. It is also described as an assumption of false when a situation is true. An example again given by Burton & Pitt (2001) is the conclusion that tested water was clean when it was actually contaminated. In most statistical tests a typical value of $\beta < 0.2$, which implies accepting a 20% risk of having a Type 2 error. The power or confidence of not having a false negative is $(1 - \beta)$ or $(1 - 20\%)$ i.e. 80%. In statistical analyses β is usually ignored if it is less than 0.5 (Burton & Pitt 2001).

Identifying patterns and associations in data is very important in environmental data evaluation. A common method to find out simple data associations is Pearson Correlation which calculates correlation coefficients between all possible data variables. Correlation analysis helps to measure the strength of association between the variables. The Pearson Correlation coefficient varies between –1 and +1. Pearson Correlation coefficient of +1 or -1 indicates a perfect prediction which can be made of one variable by using the other variable where + means a positive co-relationship and – means a negative co-relation. A value of 0 indicates that two variables considered are not correlated to each other and one variable cannot be predicted from the other by using a linear equation. To identify the correlations between two variables, Pearson correlation coefficient were calculated while Factorial Analysis was carried out to find out the complex inter correlations between the variables.

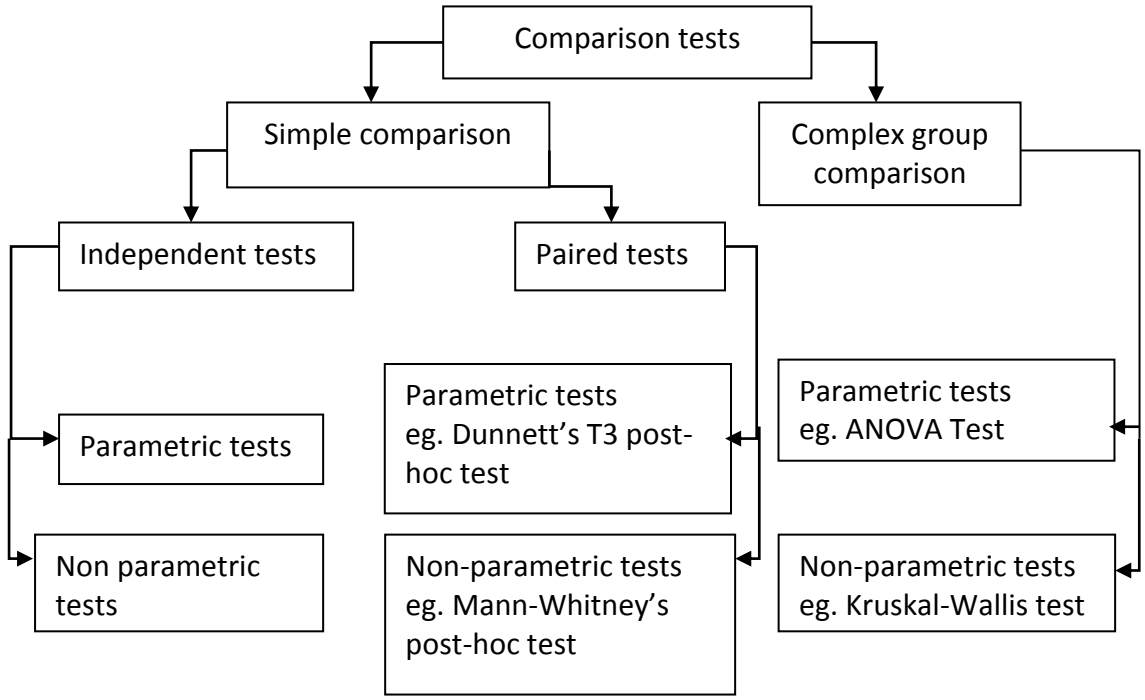


Figure 3.5 The flowchart to guide the statistical model selection procedure

3.2.1 Motivation for using multivariate statistical methods

There are many studies which show the usefulness of multivariate statistical techniques for evaluation and interpretation of data sets to get better information about the water quality related to natural and anthropogenic pollution sources. Singh et al. (2004) have used multivariate statistical techniques to evaluate spatial and temporal variations of water-quality data in Gomti River (India). The study applied multivariate statistical techniques like Cluster Analysis (CA), Factorial Analysis/Principal Component Analysis (FA/PCA) and Discriminant Analysis (DA) to explain both temporal and spatial changes in water quality. It has evaluated 24 parameters from 17,790 observations in the entire river reach.

Judite et al. (2012) also have applied multivariate statistical techniques to characterize the spatial distribution of water pollution in Lis river basin (Portugal) and to evaluate the main water pollution sources. They have evaluated 27 physicochemical and microbiological parameters related to spatial variations which have been collected in six water sampling campaigns from 16 monitoring sites. Correlation analysis and PCA are the techniques followed to describe natural and anthropogenic pollution sources and to identify monitoring sites with similar water pollution profiles.

Li et al. (2007) have evaluated 24 water quality parameters in 10 plateau lakes of Yunnan (China) using CA, FA, and PCA techniques. The same techniques have been applied by Vega et al. (1998) to analyse 22 physicochemical variables from three sampling stations along Pisuerga River in Centre-North of Spain to interpret water quality variations. Liu et al. (2003) have applied FA to 28 groundwater samples collected from wells in the coastal Blackfoot disease area of Yun-Lin, Taiwan to interpret correlations among 13 hydro-chemical parameters. Shrestha & Kazama (2007) have used CA, PCA, FA and DA to evaluate temporal and spatial variations of 12 parameters at 13 different sites in Hong Kong. Reghunath et al. (2002) have used FA and CA to analyse hydro-geochemical data for 56 groundwater samples in Nethravathi catchment in India. Wen-Cheng et al. (2011) have analysed 14 physicochemical water parameters at 8 sampling stations in Yuan-Yang Lake in north-central Taiwan using FA to extract the major underlying factors contributing to the variations among the water quality. Charkhabi et al. (2006) have also used FA for 4 water parameters along 9 stations on the Siahroud River southwest of the Caspian Sea in northern Iran to identify major pollutant sources of agricultural and urban activities. As such, the applied statistical methods were considered appropriate to investigate the variations in water quality between the patient and non-patient drinking water samples in this research.

3.2.2 Box plots

Box plot (also called box-and-whisker plot) as shown in Figure 3.6 was applied to demonstrate the data dispersion of a given variable from each sampling group. WHO standard for a given variable was also shown in each plot so that the values could be visually compared with the WHO standards. The line across a box plot represents the median value of a data range (Q2). The line below the median shows the first quartile value which is also called the lower quartile (Q1) whereas the line above the median shows the third quartile value which is also called upper quartile (Q3). The whiskers are the lines that extend from the bottom and top of the box to the lowest and highest observations inside the region defined by Q1−1.5×(Q3−Q1) and Q3+1.5×(Q3−Q1) respectively. Individual points with values outside these limits (outliers) are plotted with asterisks. Box plots were used in this analysis as they are especially useful for indicating whether a distribution is skewed and whether there are potential unusual observations (outliers) in a data set. Box-and-whisker plots are

also useful when large number of observations are involved and with two or more data sets to be compared.

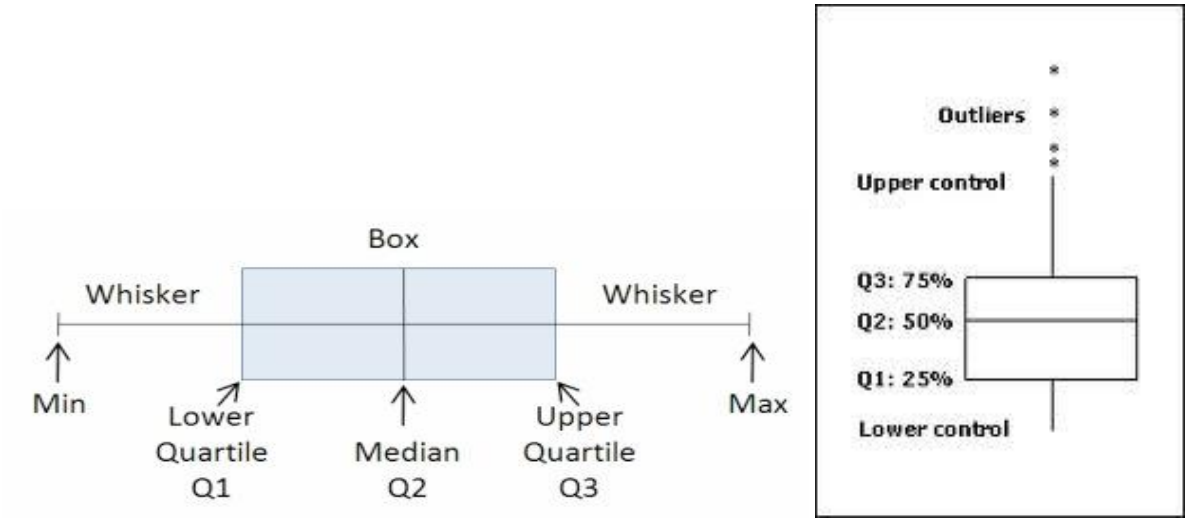


Figure 3.6 Description to box plots

(Source: Dixon 2013)

3.2.3 Univariate Analysis of Variance (ANOVA) and Dunnett's T3 post-hoc tests

ANOVA test is a complex group comparison test. It is a common parametric test which identifies the significant differences/non-differences between the groups based on average values (water quality parameter). It is especially useful when there are more than two groups of data to be compared for their significant difference in mean values.

ANOVA stands for Analysis of Variance or Univariate Analysis of Variance, however this test does not apply to variances as the name implies. ANOVA test calculates the significance via the calculation of statistical variance which gives a measure of how the data distributes itself about the mean. Unlike range that looks at the extreme values, the variance gives an idea about the distribution of data around the mean

Assumptions underlying ANOVA include that the dependent variable is normally distributed and the variances of the dependent variable are the same. When the sample sizes are comparatively small and if the populations are not normally distributed (when there are different variances among the groups), the power of ANOVA is reduced considerably. For example in this research Gampaha control area was not included in ANOVA test as this group did not have a same variance as the other four sampling groups. When the sample

populations are not normally distributed larger sample sizes may be required to produce relatively valid *p* values. In such populations, a sample size of 15 cases per group is said to be sufficient to yield fairly accurate *p* values (Green & Salkind 2005).

ANOVA test only tells whether a significant difference exists between at least two group means but it does not indicate among which groups the difference exists when there are more than two sampling groups/categories. When there are more than two sampling groups/categories, an additional test is necessary to identify which groups are significantly different. Consequently a post-hoc test is necessary to identify which pair of groups is significantly different. Post-hoc test means "after the fact" (Cunningham & Aldrich 2012), thus when significance is established, "after the fact" we try to identify which of the pairs with their means contribute to the significant difference. Dunnett's T3 post-hoc test was applied in this research to further investigate among which groups the significant differences exist.

In ANOVA test significant difference between the sampling groups were determined at $p < 0.05$ (i.e. 95% confidence level). ANOVA compares the average of a single variable of a sampling group (category) with the overall (total) average of that particular variable. The null hypothesis (H_o) for ANOVA was that average of a particular parameter in each sampling group is not significantly different (i.e. $\mu 1 = \mu 2 = \mu 3 = \mu 4$), when μ is the average of each sampling group and numerical from 1-4 represent the four sampling groups (i.e. ANU-P, POL-P, ANU-NP and POL-NP). ANOVA also assumes that the samples were selected randomly from each sampling population to represent a whole sample population. The alternative hypothesis (H_1) was $\mu 1 \neq \mu 2 \neq \mu 3 \neq \mu 4$ assuming that there were differences among the averages of each sampling group.

3.2.4 Kruskal-Wallis (KW) and Mann-Whitney's post-hoc test

Kruskul-Wallis (KW) is another group comparison test which is applied to find out significant differences/non-differences between groups. It is a non-parametric test equivalent to ANOVA which gives the groups differences based on median values. Kruskal-Wallis test compares the median of a variable in a sampling group (category) with the overall (total) median of that particular variable. In other words KW test differentiates whether the group medians of the dependent variables differ significantly from each other. Unlike ANOVA,

Kruskal-Wallis test compares two or more groups which are independent or not related and does not assume a normal distribution of data (Gaur & Gaur 2009). In literature both ANOVA and KW tests were recommended to be carried out for a conclusion so that both group mean and median values are taken into consideration.

KW test was carried out to compare whether the medians of each water quality parameter were significantly different at $p < 0.05$. The null hypothesis (H_o) in KW test was the median of each parameter in each sampling group is not significantly different assuming the samples were selected randomly from each sampling population to represent a whole sample population. The alternative hypothesis (H_1) was that there were differences in the medians among the groups.

KW gives the differences in medians within all the groups as a whole but it does not indicate among which groups the difference exist. Consequently non-parametric paired test of Mann-Whitney's test was applied to further investigate among which two groups the significant differences/non-differences in medians exist.

3.2.5 Factorial Analysis (FA)

Factorial Analysis (FA) identifies the variables that have a high correlation between each other and are independent of other variables. It is known as a technique which statistically explains the variation and co-variation among variables (Green & Salkind 2005). In this research FA was applied to classify water parameters in each sampling groups. The first step in FA is the construction of Correlation Matrix which shows correlations between variables. When there are significantly high correlations at $p < 0.05$ in Correlation Matrix, FA could be processed. On the other hand if all the correlation coefficients are 0, then the FA is known to be futile and not proceeded as there are insufficient inter-correlations between the variables (Colman & Pulford 2006). As such Correlation Matrix is an identity matrix in FA.

The second step in FA is Kaiser-Meyer-Olin (KMO) and Bartlett's test of sphericity. It is known as a diagnostic test as this test result gives a measure of sampling adequacy. The null hypothesis for KMO and Bartlett's test is that the observed data are not a sample of the multivariate normal population. If KMO and Bartlett's test values are less than 0.5 the test fails to reject the hypothesis at $p < 0.5$. According to Kaiser (1974) a measure of KMO 0.90's

is declared as marvellous, a measure of 0.80's as meritorious, 0.70's as middling, 0.60's as mediocre, 0.50's as miserable and below 0.5 is unacceptable which were secondarily considered in describing results. As such KMO and Bartlett's test was followed to find out the sampling data adequacy at $p < 0.5$.

Two indicators namely Initial Eigen Value (IEV) and the Percentage Variance (PV) are being used to decide the number of factors to be extracted which adequately represent the observed correlations. IEV is a measure of the total variance in the data explained by the factor in question. An IEV < 1 is known to explain less variance than a single variable and thus not considered as a factor. Factors having IEV > 1 are commonly used in extracting factors. Scree Plot is a visual technique to find the factors to be extracted which shows the total variance associated with each factor. Scree plot has been given its name as it resembles the scree or rubble at the base of a cliff (Colman & Pulford 2006). It shows a break between the large factors and the rest of the factors by a steep slope which gradually trail off.

Percentage Variance also gives an account of how much of variance is explained by a factor. A factor having Eigen Value above 1 has a Percentage Variance of 10% and when Eigen Value is higher above 1 the Percentage Variance goes above 10% giving more meaningful factors (Green & Salkind 2005). Therefore factors having a Percentage Variance above 10% (Eigen Value > 1) is another option used to extract factors.

Component Matrix comes in the next step of FA. It shows variables that are highly correlated falling into one group (column) of the Component Matrix and variables that are not correlated falling into different groups (columns). Accordingly different factors are seen falling into different columns in the Component Matrix. Therefore factor loadings in a Component Matrix help to identify which variables are associated with a particular factor. Component Matrix shows coefficients or factor loadings of each variable in a factor giving how much weight is assigned by each variable within a factor. For a good factorial solution, a particular variable that load high on one factor having larger coefficients will load low on all the other factors having smaller coefficients. It also means that for a good factor solution, a particular variable should load high on one factor and low on all the other factors in

Component Matrix and Rotated Component Matrix. Basically factor loadings in a Component Matrix help to identify which variables are associated with a particular factor.

Factor loadings obtained from a Component Matrix does not present a clear picture of the factor structure. Thus factor rotation maximizes the high correlations and minimizes low ones to make it easier to differentiate the factors from each other. Therefore factor rotation is done to improve the interpretability of the factors and a Rotated Component Matrix shows a simple pattern of factor loadings. Different factor rotation procedures are divided into two common methods namely, Orthogonal and Oblique methods. Varimax that is used in this analysis is the most commonly used orthogonal rotation technique available in SPSS.

In the Component Matrix, factor loadings may have different values but according to Gaur & Gaur (2009) factor loadings above 0.4 are considered for interpretation of factors. Therefore in this research too, correlation coefficients above 0.4 were taken for interpretation of factors. It is important to understand that in a Component Matrix, negative correlations are also counted (also in correlation coefficients) as the absolute value is what counts in correlations.

To show factor results graphically, Component Transformation Matrix is used. Component Transformation Matrix is produced by un-rotated matrix divided by rotated matrix. When the factor solution has more than two factors, a three-dimensional plot is obtained in Component Transformation Matrix. In factor solutions, factors are not interpreted by a single variable as a factor consisting of one variable will have Percentage Variance < 10%.

After FA, Scale Reliability test was applied to find out whether the factor variables are reliable in explaining a given factor. The reliability test gives a measure of how much the variables measure the derived factor. It is measured by an indicator called Cronbach’s Alpha which measures the correlations between the variables in each factor. Higher Cronbach’s Alpha value means higher reliability of the variables in a factor. Cronbach's Alpha value of 0.7 and above is considered to be acceptable and a value of 0.8 and above is considered to be good and highly reliable (Kaiser 1974). The reliability test also gives how much of reliability of the scale changes when an item is eliminated from the factor. When a variable is eliminated from a factor and if the Cronbach's Alpha value drops, it is said that the

variable is indicative of the reliability of that factor. More the reliability value drops from its original value, the more reliable is that variable in explaining the given factor.

A reasonable sample size is said to be necessary to extract factors. For this reason some authorities have recommended a minimum of five times as many cases (rows) as variables (columns) for analysis (Colman & Pulford 2006). In another 10 cases per variable to an overall sample size of at least 300 cases are recommended (Norusis 2010). According to Gaur & Gaur (2009), a sample size of less than 100 is not very suitable for conducting FA but a sample size of 200-300 is adequate for proper analysis and a sample size above 500 is excellent. As such the primary data set collected by the candidate is adequate for the analysis in this research.

3.2.6 Discriminant Analysis (DA)

Discriminant Analysis (DA) is another statistical tool which evaluates group classifications. It classifies the groups according to linear combinations of variables to identify the correct group classifications. As such DA is another statistical tool which evaluates results of a group classification based on all the combinations among variables. It shows how much of the groupings are correct in their original classifications in terms of percentages. For example in this research, DA showed how much the groupings which were used to analyse data were correct as a percentage and also whether they have similarities with other groups. Basically that gave an idea if Anuradhapura and Polonnaruwa patient and non-patient classifications (in four groups) were correct. DA gave an idea of whether those four groups discriminate against each other. In other words DA shows how much of a percentage of samples can be classified under own groups and whether there are similarities with other groups.

SPSS software was used in all these statistical analyses

3.3 Summary

This chapter described the study area, drinking water sampling numbers and their locations. It gave justifications of how the sample parameters were selected based on CKD endemic evidence in the literature. The statistical tools applied in the research were based on the previous studies to find out pollution sources in other applications. Some previous researches on water pollution analysis using similar statistical procedures were introduced

in this chapter. A brief introduction of each statistical tool was given and a flowchart was given to simplify the selection procedure. ANOVA and Dunnett's T3 post-hoc tests were used to identify group differences based on mean values. Kruskal Wallis (KW) and Mann-Whitney's post-hoc tests were used to identify group differences based on median values. Chemical parameters do not exist singly in natural situations due to chemical interactions. Therefore combinations of water parameters also needed to be identified. Factorial Analysis was the tool which was applied to identify those combinations. Discriminant Analysis was used to identify correct groupings.

4 METHODOLOGY- II : RAINWATER HARVESTING (RWH) TANK ESTIMATION

Due to polluted groundwater in CKD endemic areas of Sri Lanka, rainwater harvesting (RWH) is being considered as a viable drinking water substitute in this research. Methodology was further extended to estimate rainwater tank sizes using Mass curve method. As such RWH tank estimations for eight rainfall stations located within close proximity to CKD patient households in Anuradhapura and Polonnaruwa districts were carried out in this study. Those rainfall stations were: AN487, AN109B, AN487A and AN410A from Anuradhapura district and PL93B, PL134A, PL141A and PL162 from Polonnaruwa district. The locations of these rainfall stations are shown by yellow pins in Figure 4.1 while CKD patient and non-patient water sampling locations are shown by red crosses. Daily rainfall data available for recent past 10-11 years (2001 to 2011) were obtained from the Department of Meteorology, Sri Lanka for RWH tank estimations.

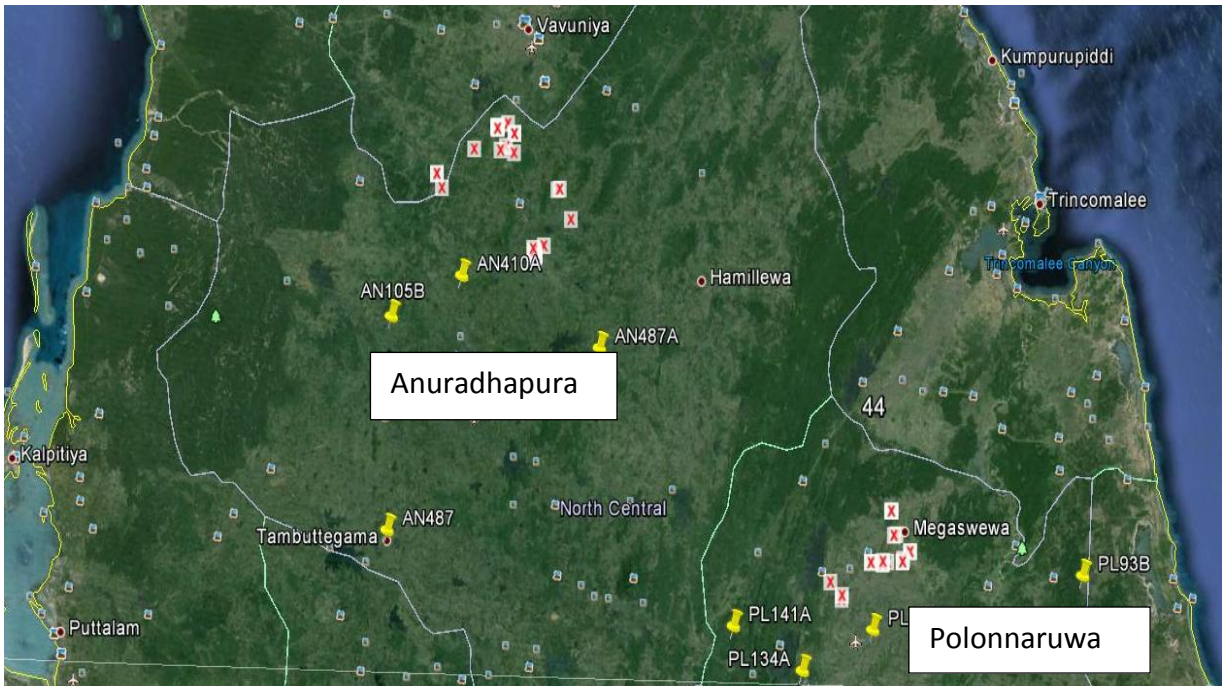


Figure 4.1 Rainfall stations marked in yellow pins and CKD patient and non-patient sampling locations marked with red crosses

4.1 Mass curve method

Optimum rainwater tank sizes were calculated for each rainfall station using Mass curve method. Mass curve method was originally proposed by Rippl (1883) and has been used by many researchers (e.g. Handia et al. 2002, Goel & Kumar 2005).

This method calculates the required tank volume (storage) depending on household demand and rainwater supply of a given location. Optimum rainwater tank sizes for the given locations were calculated based on monthly and daily rainfall data. To calculate the optimum tank sizes using Mass curve method, a hydrological year which starts from the first rainy day of the rainy season after the longest dry period/season is considered. It is assumed that the rainwater tank was almost empty by this day due to the preceding dry period. Starting from the first day of rainfall, cumulative water supply to the tank is plotted in the mass curve graph. On the same graph, cumulative water demand of the household (assuming a family using water from this tank) is also plotted throughout the hydrological year. If the tank is of adequate capacity, cumulative water supply by the tank should not go below the cumulative water demand of the household at any time of the year or at the end of the hydrological year. When cumulative demand of household and cumulative rainwater supply of the tank is plotted for a hydrological year, maximum difference between the cumulative supply and cumulative demand gives the tank size required for the household (Figure 4.2).

Extra water need not be left in the tank at the end of a hydrological year as there will be rain to fill the tank again at the beginning of a new hydrological cycle. Optimum tank thus means the tank will be sufficient to provide water to the family throughout the year while it is not extra-large to hold water of un-necessary capacity. Larger tanks than required will incur unnecessary construction costs and make them of unmanageable sizes. If there is any water left in the tank at the end of a hydrological year that volume can be subtracted from the estimated tank size to calculate the optimum tank volume required for the household (H_1-H_2) as shown in (Figure 4.2). As such the optimum tank size is obtained by the greatest difference between the cumulative supply and cumulative demand (most storage) minus the least difference between the cumulative supply and cumulative demand (least storage)

which occurs at the end of the dry/wet period when a new annual rainfall cycle begins (Dawe 2001).

When drier periods (with less rain) are used to estimate tank sizes, bigger tank sizes are obtained. Hydrological year with a minimum rainfall in the past 10 years were used to calculate tank sizes for each station as the estimated tanks need to serve any such future dry spells. The rainfall immediately preceding this drought was taken as the start of the hydrological year. Then the tank sizes estimated need to be of sufficient capacity to provide water to the household of concern during the long dry period. Theoretically this tank represents rainwater quantity which will be adequate to supply water during the dry period of the year without a water shortage.

Historical rainfall data are used as a template for calculation of RWH tank systems on the assumption that rainfall pattern in the future will be similar to past rainfall patterns. As the rainfall pattern in future is not readily predictable, rainfall data for at least 10 previous years are used to increase the degree of reliability in predicting future rainfall (Oti & Skinner 2012). The household water demand may also vary depending on many criteria such as user-behaviour and yearly variations and within year variations. For example children may demand less water than adults and the family will have a higher demand during the dry periods than wet periods. However for ease of calculation it is assumed that household demand remains constant throughout the year and from year to year.

To calculate rainwater tank sizes using Mass Curve method, Equations (4.1) and (4.2) were used (Farreny et al. 2011). Equation (4.1) gives the yearly water demand of a household whereas Equation (4.2) gives the rainwater supply to the household depending on the available catchment surface and yearly rainfall.

$$D = N \times C \times 365 \qquad (4.1)$$

$$RWHP = A \times R_c \times R \qquad (4.2)$$

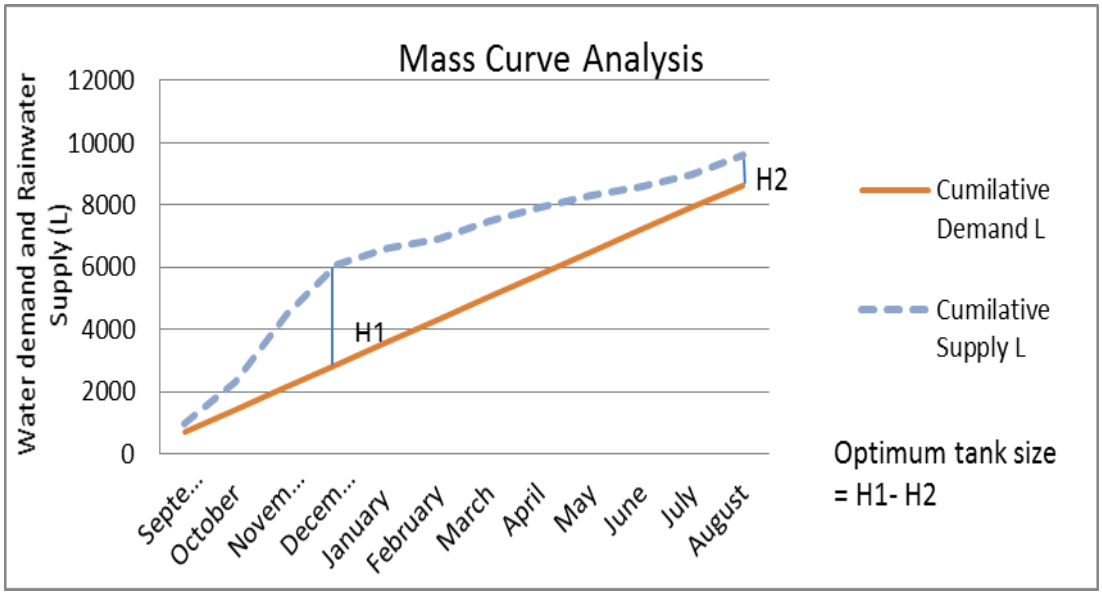


Figure 4.2 Graphical illustration of tank size estimation using Mass curve method

(Source: Roebuck 2006)

In Equation (4.1), *D* is the yearly water demand for all users in a household (L/year). It is a function of the water requirement of all the household members. *C* is the consumption per capita per day in the household (L/capita/day) and *N* is the number of people in household using water from this source. As per capita consumption is calculated for a day, it is multiplied by 365 to estimate the requirement for one year. In Equations (4.2), RWHP is rain water harvesting potential (m^3/year) or the rainwater supply to the household. It is a function of the catchment surface area available to capture rainfall as well as the amount of rainfall. Catchment surface area *A*, which is also called the runoff surface area (m^2). *R* is the rainfall (mm/year). *Rc* is the runoff coefficient (dimensionless) of the catchment surface, which indicates the portion of rainfall that becomes useful after it falls on the surface. *Rc* is described in detail later.

The effectiveness of the Mass curve is known to depend on the accuracy of determining the starting month or day of the hydrological year when rainy season starts after a long spell of dry season (Ngigi 1999). There is a specific rainfall pattern with north-eastern monsoonal rains falling in northern part of Sri Lanka including NCP during October to March. Therefore the hydrological year starts in October or November for each station depending on fluctuation of rainfall initiation.

Although individual drinking water requirement may vary from person to person, a supply level of 10 L/day/person is found to be more than enough to meet potable purposes (Oti & Skinner 2012). However domestic water consumption is known to depend on the distance to the water source from home and if the water source is up to 1 km away, domestic water consumption is known to be 4–8 L/day/person (FAO 2011). Therefore in tank estimations daily drinking water requirement was taken as 6 L/day/person.

The commonly used method for calculating household water demand is by summing up individual water demands by the number of occupants in the household. As such the maximum expected family requirement varies depending on family size. In NCP the average household number is four (NRSL 1991) and therefore an average family size of four was used in RWH calculations.

Rainfall data intervals based on hourly, daily or monthly are typically employed in rainwater harvesting estimations. However the data requirement and complexity of RWH models tend to increase as the time-step decreases, and therefore the optimum approach is to use the largest time-step possible that is still capable of producing sufficiently accurate results (Fewkes & Butler 2000). Monthly rainfall data are known to be preferable over daily data due to reduced number of data required to be manipulated (Eric & Latham 1992). However, monthly data are known to have inaccuracies to capture rainfall fluctuation, while sub-daily models are complex with high data requirement (Latham 1983, Roebuck 2006). According to Fewkes & Butler (2000) monthly data are recommended to be applied when sizing large stores but not for domestic RWH systems. In this study both daily and monthly rainfall data were used in tank size estimations. The tank sizes obtained were compared for their significant differences statistically using t-test. The null hypothesis was that the monthly and daily models do not indicate any significant differences in tank volume calculations at $p < 0.05$ (i.e. 95% confidence level).

A limitation of Mass curve method is that it cannot be generalised for all the locations due to uniqueness of rainfall pattern used to generate it (Oti & Skinner 2012). As such Mass curves need to be designed for locations having varying rainfall amounts and patterns.

4.2 Dimensionless graphs

Dimensionless graphs are an extension of Mass curve method (Oti & Skinner 2012). They are constructed by estimating tank storages as a percentage of average annual supply against various demands, also expressed as a percentage of average annual supply. Dimensionless graphs work for all demands, for any roof material with any runoff coefficient regardless of the dimensions used to calculate it (Dawe 2001). The practical use of dimensionless graphs is that they can be used to determine the tank sizes for any household irrespective of rainfall supply or demand. Therefore Dimensionless graphs were also designed for the rainfall stations in the CKD endemic area.

4.3 Runoff surface calculation and runoff coefficient

Roofs are commonly used as runoff surfaces in rainwater harvesting. The roofing materials used in the houses of CKD endemic areas of NCP include clay tiles, tin sheets, asbestos and straws. Asbestos fibres are dangerous to health when inhaled, however it is not known to pose a risk as a rainwater catchment (Australian drinking water guidelines 2004). Tin sheets are preferable over other material for RWH; however straws as a roofing material are not suitable as a catchment surface to collect rainwater. As such polythene sheet is proposed is this research to be used as runoff surface as many of the households in NCP do not have proper runoff surfaces to collect water. Polythene sheets are cheap and locally available. Polythene material could be fixed with a simple frame and tilt at a height to match with the guttering and carry water directly to the tank. In some instances where houses already have suitable roofing material and area, it is proposed to use the existing roofs as a runoff surface. Even if houses have sufficient roofing areas but are not clean enough for rainwater collection, polythene sheets can be overlain on the roofing surface to act as a runoff surface.

When estimating the required runoff surface area for a given household, the runoff surface area should have rainwater harvesting potential (RWHP) to satisfy the yearly water demand (D) of a household within a hydrological year. As such Equations (4.1) and (4.2) above were equated with a consistent unit in order to estimate the minimum runoff surface area (A) as shown in Equation (4.3) below.

$$A = \frac{N \times C \times 365}{R_c \times R} \qquad (4.3)$$

In rainwater collection, about 25% of the rainwater is assumed to be lost by evaporation and first flush (Ahmed 1999). The runoff coefficient (*Rc*) gives the portion of rainfall that becomes useful in RWH after losses. The losses occur due to spillage, leakage, surface wetting and evaporation (Villarreal & Dixon 2005, Singh 1992, Farreny et al. 2011). Other factors accounting for *Rc* are intensity of the rainfall event, antecedent moisture, prevailing winds and orientation of roofing. Different roof materials are also found with diverse runoff behaviours due to distinct retentions, textures and weathering processes to cause different *Rc* values (Göbel et al. 2007). Architectural factors of surfaces such as slope, surface depressions, leaks/infiltration and roughness also determine *Rc* values for different roofs (Farreny et al. 2011). However the most important abstraction is known to be interception which is defined as the rainfall that wets and sticks to above surface objects until it is returned to the atmosphere through evaporation (Rebert 1998). *Rc* is a dimensionless value which is given in Equation (4.4) by Farreny et al. (2011).

$$Rc = R_p/P \qquad (4.4)$$

where, R_p = total runoff per year (rainwater harvesting potential) as a depth (mm/year), P = annual depth of rainfall (mm/year). Estimates have given the roof *Rc* values to be in a broad range of 0.7 – 0.95 for relatively frequent storms based on the degree of imperviousness and infiltration capacity of the runoff surface (Farreny et al. 2011). According to Ree et al. (1971) *Rc* is known to vary from 0.3 for ground catchments to 0.9 for tin roofs but is in the range of 0.7 to 0.9 for most roofing systems. The global *Rc* for different roofs has been estimated by means of runoff models taking into account runoff of each rainfall event, and dividing the total runoff per year using the above equation.

In this study, *Rc* value was taken as 0.75. Even though the proposed rainfall collection material of polythene is expected to have higher R_c value, the applied lower value of 0.75 was assumed to compensate the first flush diversions, losses due to leakage, spillage and evaporation.

The least rainfall in the past 10 years was used to calculate the minimum runoff surface area (*A)* of a given rainfall station. When the minimum runoff surface area (*A)* calculations were done using the Equation (4.3), in some cases it was noted that the calculated surface areas were not adequate to fill tanks. This was made apparent during Mass curve analysis when the calculated areas were applied the cumulative demand exceeded the cumulative supply in a hydrological year. In those calculations the minimum surface area needs to be increased till cumulative demand met the cumulative supply in a hydrological year. In such instances, the estimated minimum surface values were increased by 0.5 m^2 each time till the cumulative demand and supply values equated.

In this research rainwater tank estimations and runoff surface area estimations were carried out for each rainfall station/area in Anuradhapura and Polonnaruwa using daily and monthly rainfall data. As shown in Figure 4.1, it can be noted that the rainfall station AN487 is somewhat away from the CKD locations, otherwise other stations in Anuradhapura are closely located to CKD endemic locations. In Polonnaruwa district the rainfall stations are not very close to CKD locations due to non-availability of nearby rainfall stations.

4.4 Reliability analysis

The major drawback of Mass Curve analysis method is “reliability” not being inherently embedded in the results. Therefore reliability of the tank size estimations was carried out independently. Reliability of a tank is explained as the portion of demand that is met by supply, which is also known as the performance of a RWH system (Gould & Nissen-Peterson 1999, Fewkes & Butlers 2000). Performance of the RWH system is expressed either by time or volumetric terms (Fewkes & Butler 2000). Reliability level is known as a measure of how well the system meets the total demand based on time or volume considerations. Time reliability is a measure of the amount of time for which the tank supplies the total amount of water in demand. Volumetric reliability is the portion of demand that is met by harvested water, which is defined by the total volume of harvested water divided by the total water demand (Liaw & Tsai 2004). For example, a reliability level of 95% is meant to supply 95% of the total volume demanded (volume reliability) or that to supply the full amount demanded 95% of the time (time reliability). The volumetric reliability considers all the water supplied by the tank, whereas the time reliability does not take into account the water supplied

during a time step if the total demand cannot be met. Therefore storages required for time reliability are known to be greater than those for volume reliability (Eric & Latham 1992). Thus a limitation of the time reliability indicator is that it can give poor time reliability results even when a system meets a certain demand. As such volumetric reliability is a better reliability measure over time reliability, and therefore volumetric reliability was applied to analyse the reliability of the estimated tank sizes.

Hundred (100) per cent time reliability is known to automatically meet 100% volume reliability and calculations based on a small time interval, e.g. daily data are independent of the reliability type (Eric & Latham 1992). Volumetric reliability of the tank sizes were calculated using Equation (4.5). These volumetric reliability values, obtained as percentages of water demand, were plotted against tank sizes.

$$\text{Volumetric reliability of a tank} = \frac{\text{Total volume of harvested water by that tank}}{\text{Total water demand}} \tag{4.5}$$

4.5 Sensitivity of the developed Mass Curve model

Sensitivity analysis was carried out for each rainfall station tank estimation for varying R_c values between 0.5 and 0.9, varying per capita consumptions between 6 and 10 L/day and varying household sizes between 4 and 6 to find out the trends of the storage capacities.

4.6 Summary

Mass curve method was selected for rainwater tank estimations as a part of harm minimization scheme. However there is a requirement to determine the tank sizes for each household in the area based on family demand. As such dimensionless graph was introduced to handle variable demands. A dimensionless graph designed for a rainfall station can be applied to determine the tank size of a family located near to that rainfall station depending on the demand, and the catchment surface features (catchment surface area and R_c). Reliability analysis was introduced as a measure to interpret the performance of the tanks for the portion of demand that is met by supply. Sensitivity analysis of tank estimations was described which gave the tank size variations depending on catchment R_c values, per capita consumptions and household numbers.

5 METHODOLOGY III : USE OF NATURAL ADSORBENTS FOR FLUORIDE REMOVAL IN WATER

Organic adsorbent materials were selected for fluoride removal considering its suitability for human consumption, availability in CKD endemic areas and simplicity of application. As such the materials tested for fluoride adsorption were turmeric rhizome powder (*Curcuma longa*), ginger rhizome powder (*Zingiber officinale*) and powdered curry leaves (*Murraya koenigii*). All these plants are naturally grown in CKD endemic areas of NCP as well as other dry areas of Sri Lanka and are commonly used as herbs and spices. Turmeric powder and ginger powder is obtained by grinding their tubers. Powdered curry leaves were obtained by crushing the leaves of the particular plant.

Raw turmeric and ginger tubers and curry leaves were procured from the market. Raw turmeric and ginger tubers were thoroughly washed with distilled water to remove impurities and the external covers were peeled off. Curry leaves were also processed for the experiment in the lab by thoroughly washing with distilled water to remove impurities. They were all oven dried for 24 hours at 120°C and then grinded separately by mechanical and manual devices. Afterwards the fine powders were sieved through 350 and 250 µm sieves in order to obtain particles between these two sizes. To increase the area of adsorption it is preferable to have smallest possible particle size. However the aim of this research was to introduce a suitable fluoride adsorption material to the communities in Sri Lanka. Therefore this particle size was considered suitable as can be obtained by mechanical or manual grinding at household level. These samples were kept in airtight containers for subsequent testing.

Anhydrous sodium fluoride (from Merck, Darmstadt, Germany) was used to prepare fluoride solutions. All chemicals used in the study were of analytical reagent grade. Stock sodium fluoride (NaF) solution was prepared according to the calculations as follows:

Atomic weight of Na = 22.989 g, atomic weight of F = 18.989 g; so the molecular weight of NaF = 22.989 + 18.998 = 41.987 g.

Weight of NaF required to make 100 mg/L fluoride stock solution =

$$\frac{\text{NaF } (41.987\text{g}) \times 100 \text{ mg}}{\text{F } (18.998\text{g}) \times 1000 \text{ mg/g}}$$

$$= 0.221 \text{ g of NaF in 1L water}$$

Anhydrous NaF of 0.221 g was weighed in a weighing-tube using a chemical weighing balance with accuracy up to ±0.001 g. This was added to a Pyrex Conical flask of 1 L and filled with MilliQ (double distilled) water up to 1 L level to obtain 100 mg/L fluoride stock solution. This solution was then thoroughly mixed using a magnetic stirrer for 30 minutes. Afterwards the necessary dilutions were prepared by diluting this stock solution. For example to prepare 1 mg/L fluoride solution, 5 mL of stock solution was taken to a Pyrex Elementary flask of 500 mL and filled with MilliQ water up to 500 mL level. Other dilutions of 2, 3, 4 and 5 mg/L fluoride solutions were also prepared the same way by taking 10, 15, 20 and 25 mL stock solutions into Pyrex Elementary flasks and filling with MilliQ water up to 500 mL level. These solutions were then thoroughly mixed using magnetic stirrer. Magnetic stirring speed of 340 rpm for 30 minutes was sufficient for them to mix well.

The adsorbents turmeric, ginger and curry leaf powder were subjected to preliminary experiments to identify the adsorbent with highest fluoride adsorption capacity. Equal weights of 0.2 g of each adsorbent material were placed into 3 columns as shown in Figure 5.1. Each column was filled with equal volume of fluoride solution (25 mL) having 10.5 mg/L concentration of fluoride to carry out the experiment. The adsorbent material which adsorbed the most fluoride was selected as the suitable adsorbent for further investigation. Room temperature was 24±2°C and pH was maintained between 6 and 6.5.

Out of all these adsorbents, turmeric showed the highest adsorption capacity over ginger and curry leaves. Therefore turmeric powder was selected as the adsorbent material and was subjected to further detailed batch and column experiments.

Figure 5.1 Experimental setup for preparation and selection of best adsorbent material

5.1 Batch experiments

Batch experiments were conducted to find out the kinetics of adsorption of fluoride on turmeric which is an important design parameter for predicting the rate at which adsorption would take place. Batch experiment helps in studying the thermodynamics of adsorption process and thereby to measure adsorption parameters like contact time, temperature, adsorbate and adsorbent doses and pH.

In this experiment 500 mL NaF solution was taken to PVC bottles and adsorption experiment was conducted by adding a known weight of turmeric (say, 0.2 g). A room temperature of 24±2°C was maintained throughout the experiment. The mixture solution was subjected to magnetic stirring as shown in Figure 5.2 at a uniform speed. Two speeds of 230 and 640 rpm were tested for this experiment. At 230 rpm more time was taken to reach equilibrium while at 640 rpm, equilibrium was reached faster and thus sampling intervals were pretty short to be maintained. Therefore a speed of 340 rpm was chosen as adequate. Sample amounts of 25 mL were taken out after each time interval. These samples were filtered using syringe filtration (standard 25 mm filters) to separate the adsorbents. This filtered solution was used to measure the change of fluoride concentration compared to initial concentration. Samples were collected at different time intervals between 5 to 120 minutes. The pH of each solution was adjusted between 6 and 6.5 to have correct fluoride readings and to eliminate the interference of other ions. To fix the pH values, TISAB sachet (Total Ionic Strength Adjustable Buffer) was added to each supernatant sample of 25 mL and stirred well. TISAB sachet was also supplied by Merck, Darmstadt, Germany.

Figure 5.2 Experimental setup to show the batch experiments

Fluoride concentration of each sample was measured by using a Laboratory Combination ISE Fluoride Probe (ISEF121AP – solid-state crystal membrane sensor type porous Teflon annular ring probe with a non-refillable driTEK gel filling solution, with a range of 0.01 mg/L ($1x10^{-6}$ M) to 19,000 mg/L (1 M) and with a temperature range of 5-50°C for continuous use with an Integrated Thermistor).

Batch adsorption experiments were conducted to investigate the effect of various adsorbent amounts, adsorbate (fluoride) concentrations, pH and temperature. To find out the influence of pH value on fluoride adsorption, 0.1N HCl or NaOH were added to the original fluoride solution to adjust the pH of the solutions. When the fluoride adsorption was measured as a function of temperature, the prepared samples were placed in a water bath under fixed temperature and fluoride concentration changes were measured according to the procedure given above.

When the initial concentration of each adsorbate (fluoride) solution was known and equilibrium concentration was measured, the amount of fluoride adsorbed was calculated using Equation (5.1):

$$q_e = \frac{(C_i - C_e)\,V}{W} \qquad (5.1)$$

where qe = fluoride adsorbed per unit mass of adsorbent at equilibrium (mg/g), = initial fluoride concentration (mg/L), = fluoride concentration at equilibrium (mg/L), V = volume of fluoride solution (mL), W = mass of adsorbent used in the experiment (g). Similarly fluoride

adsorbed per unit mass of adsorbent (qt) at time t (mg/g) can be expressed as in Equation (5.2):

$$q_t = \frac{(C_i - C_t)\,V}{W} \qquad (5.2)$$

where qt = amount of fluoride adsorbed per unit mass of adsorbent at any time t (mg/g), = fluoride concentration at time t (mg/L). The removal percentage (R %) of fluoride is defined as the ratio of difference in fluoride concentration before and after adsorption (Ci−Ct) to the initial fluoride concentration (Ci) given in Equation (5.3).

$$R(\%) = \frac{C_i - C_t}{C_i} \times 100 \qquad (5.3)$$

5.1.1 Thermodynamics of adsorption (equilibrium modeling and adsorption isotherms)

The distribution of fluoride between the liquid phase and the solid phase is a measure of the position of equilibrium in the adsorption process and can be interpreted by thermodynamics of adsorption. Thermodynamics give the relationship between the amount of adsorbate adsorbed at constant temperature and its concentration in the equilibrium solution. This relationship was expressed by adsorption isotherms. Experimental batch adsorption data were analysed with two well-known sorption isotherms: Langmuir and Freundlich isotherms in order to find out what mechanism of adsorption was described by this adsorbent. The experimental data were fitted to Langmuir and Freundlich Isotherms and the best fit model was obtained through regression.

Langmuir sorption isotherm is used to interpret monolayer coverage of the sorption surfaces and assumes that sorption takes place on a structurally homogeneous surface of the adsorbent (Langmuir 1916). The assumption in this model is that adsorption layer will be one molecule thick and each of the adsorbent molecules is capable of adsorbing one molecule of adsorbate. Also it indicates adsorbent material has a specific number of identical sites on its surface for adsorbing adsorbate. Furthermore, it is assumed that all the adsorption sites have equal affinities for molecules of the adsorbate and the presence of adsorbed molecules at one site will not affect the adsorption of molecules at an adjacent site. Langmuir isotherm is expressed as Equation (5.4) (Langmuir 1916).

$$q_e = \frac{Q_0 b C_e}{(1+b C_e)} \qquad (5.4)$$

The linear form of the Langmuir isotherm is expressed as Equation (5.5).

$$\frac{1}{q_e} = \frac{1}{Q_O} + \frac{1}{bQ_O Ce} \qquad (5.5)$$

where Q_o = monolayer capacity of the adsorbent (mg/g) or the maximum amount of the fluoride ion per unit weight of turmeric to form a complete monolayer on the surface of adsorbent, b = Langmuir adsorption constant (L/mg) related to the affinity of the binding sites. Q_o represents a particle limiting adsorption capacity which can be used to compare adsorption performance, particularly in case where the sorbent does not reach its full saturation in experiments (Ghorai & Pant 2004). A linear plot of $1/q_e$ versus $1/C_e$ indicates the applicability of Langmuir adsorption isotherm and the values of b and Q_o can be calculated from the slope and intercept of the plot, respectively.

Freundlich isotherm is derived in modeling multilayer sorption where sorption takes place on heterogeneous surfaces. It is based on the assumption that adsorbent has a heterogeneous surface composed of different classes of adsorption sites (Freundlich 1906). The Freundlich isotherm is given by Equation (5.6) (Freundlich 1906).

$$q_e = k_f C_e^{1/n} \qquad (5.6)$$

Taking log on both sides of Equation (5.6), Freundlich equation is written as Equation (5.7)

$$\log q_e = \log k_f + \frac{1}{n} \log C_e \qquad (5.7)$$

where k_f = Freundlich constant related to adsorption intensity which is indicative of surface heterogeneity of the sorbent and n = empirical parameter. If $1/n < 1$, bond energies increases with surface density, and if $1/n > 1$, bond energies decreases with surface density. When $1/n = 1$ all surface sites are equivalent. A plot of the log q_e versus log C_e gives a straight line and k_f and n values are calculated from the intercept and slope of this straight line, respectively. The intercept and slope are indicators of adsorption capacity and

adsorption intensity respectively of the adsorbent. The adsorption data were plotted into Freundlich isotherm model to perceive the suitability of the model.

5.1.2 Kinetics of adsorption

One of the most important factors in designing an adsorption system is predicting the rate at which adsorption takes place. This rate depends on the physical and or chemical characteristics of the adsorbent and is determined essentially by the three consecutive steps of adsorption (bulk diffusion, film diffusion and pore diffusion) which are also the rate-limiting steps. Generally, both pore and film diffusions are considered to be the major factors controlling rates of sorption from solution by porous adsorbents (Benefield et al. 1982, Weber 1985).

Lagergren pseudo first-order and pseudo second-order kinetic models were used to express the mechanism of fluoride adsorption onto surface of turmeric. These models give an account of time of contact to be allowed between the adsorbent and adsorbate to reach equilibrium depending on the mechanism of fluoride adsorption. The rate constants for adsorption were determined using each model. The experiments were conducted with initial fluoride concentrations of 1, 2 and 5 mg/L.

Lagergren pseudo first-order kinetic model is presented as in Equation (5.8) (Lagergren & Svenska1898).

$$\log(q_e - q_t) = \log q_e - \frac{k_l}{2.303} t \qquad (5.8)$$

where k_l = rate constant of first order adsorption (min^{-1}). Using the equation above by plotting adsorption results with log (q_e-q_t) versus t, Lagergren pseudo first-order kinetic constant (k_l) and q_e values were determined.

Pseudo second-order kinetic model is presented as Equation (5.9) (Ho & McKay 1999, Mc Kay 1984).

$$\frac{dq_t}{dt} = k_2(q_e - q_t)^2 \qquad (5.9)$$

where k_2 = rate constant of pseudo-second-order chemisorption (g/mg.min). For boundary conditions (t = 0 to t = t and q_t = 0 to q_t = q_t), pseudo-second-order kinetic model is given by Equation (5.10).

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{1}{q_e} t \qquad (5.10)$$

Using the equation above when adsorption results were plotted with t/q_t versus t pseudo second-order rate constant q_e and k_2 values were determined for each fluoride concentration from the slope and the intercept of corresponding plot, respectively.

Intra-particle diffusion model was applied in order to find out whether intra-particle diffusion was involved in the adsorption process. For that the amount of fluoride adsorbed per unit mass of adsorbents, (q) was plotted as a function of square root of time, ($t^{½}$). The rate constant for intra-particle diffusion was obtained using the Equation (5.11) (Ghorai & Pant 2005).

$$q = k_p t^{1/2} \qquad (5.11)$$

where K_p = intra-particle diffusion rate constant (mg/g.min).

5.2 Column experiments

Column experiments are done to predict dynamic performance of an adsorbent in a continuous flow system. Column experiments were necessary to find out the predictability of contact time necessary to achieve the equilibrium capacity of adsorbent material of turmeric powder in a fixed bed system. It gave a measure of continuous operation of the adsorbent in a packed column of the adsorbent in cyclic sorption/desorption process. The column experiments were also used to study the effect of process parameters such as inlet flow rate, initial fluoride concentration and bed height. Different adsorption kinetics models were also studied for removal of fluoride with turmeric using column experiment data.

Fixed-bed column studies were carried out in glass columns of 2.5 cm internal diameter and 55 cm height. The amounts of turmeric considered as bed material were 0.75, 1.5 and 2.25g. Turmeric beds were flushed several times with distilled water to ensure a close packing of

the bed to avoid cracks, channels or voids during the flow of fluoride solution through the column. In the experiment, fluoride solution was fed through the bed in a downward direction and the effluent was collected at the bottom through a 2 mm diameter orifice. Samples of the outlet solution were collected at definite intervals of time to examine its fluoride concentrations. Initial fluoride concentrations used were of 1.45, 2.45, 3.09 and 6.30 mg/L and flow rates tested were 0.33, 0.66 and 0.99 mL/min. To have uniform flow rates in each experiment, a peristaltic pump was used (Schematic diagram of the column experimental setup is given in Figure 5.3. The room temperature at the time of column experiments was 24± 2°C.

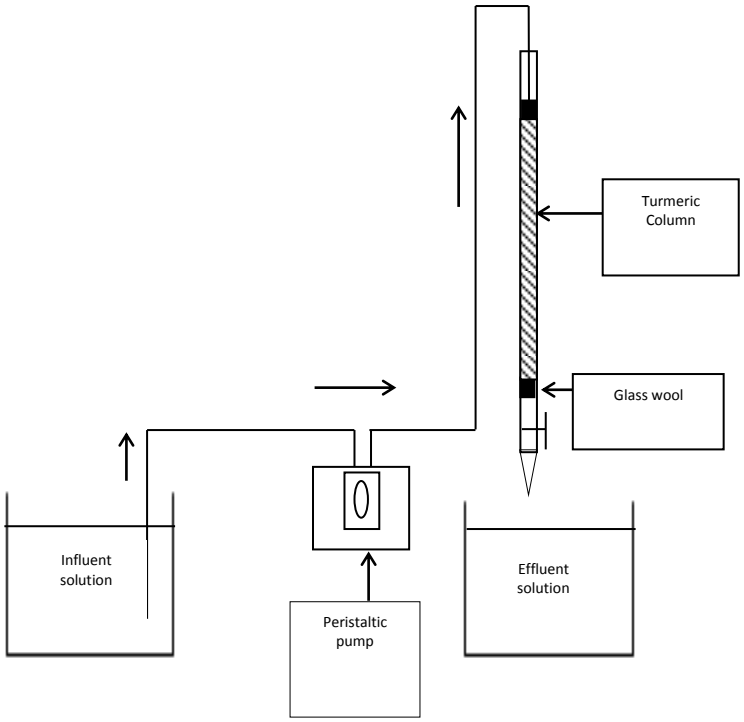


Figure 5.3 Schematic diagram of the column experimental setup

5.2.1 Breakthrough analysis

In a fixed bed adsorption system, the adsorbent located closest to influent saturates first. This saturated adsorption zone moves gradually down as time passes and then approaches the exit of the bed. When the saturation zone has moved through the column, the concentration of the adsorbate at the exit becomes equal to the influent concentration.

When a plot is drawn with exit concentration as a function of lapse time, it takes the shape "S" and therefore called an S-curve or breakthrough curve. The time taken for the effluent

concentration to reach the influent concentration is called breakthrough time. The shape of a breakthrough curve depends on flow rate, concentration of influent solution and the column properties like bed height and bed diameter. Also the area under a breakthrough curve gives the total quantity of fluoride adsorbed for a given feed concentration.

Breakthrough curves are usually expressed in terms of normalized concentration defined as the ratio of the outlet concentration (C_t) to the inlet concentration (C_o) as a function of time (in minutes). Breakthrough capacity which was given by weight (mg) of fluoride adsorbed per gram of turmeric can be calculated by using the Equation (5.12).

$$Breakthrough\ capacity = \frac{Fluoride\ amount\ adsorbed\ on\ adsorbent\ bed(mg)}{mass\ of\ absorbent\ in\ bed\ (g)}$$

$$= \frac{Breakthrough\ time\,(min) \times Flowrate\left(\frac{mL}{min}\right) \times Feed\ concentration\ \left(\frac{mg}{mL}\right)}{Mass\ of\ adsorbent\ in\ bed\ (g)} \qquad (5.12)$$

5.2.2 The Bed Depth Service Time (BDST) model and critical bed depth

BDST model has been proposed by Bohart and Adams (1920) to interpret the relationship between bed depth and breakthrough time for fixed-bed adsorption columns. It is one of the most widely used methods to predict the bed capacity of a column by utilizing different breakthrough values (Han et al. 2007). The modified version of the BDST model is given by Equation (5.13) (Kanadasanet et al. 2010).

$$t = \frac{hN_0}{VC_0} - \frac{1}{k_a C_0}\ ln\left(\frac{C_0}{C_B} - 1\right) \qquad (5.13)$$

where C_o = initial concentration of solute (mg/L), C_B = desired concentration of solute at breakthrough (mg/L), k_a = adsorption rate constant (L/mg/min), N_o = adsorption capacity per unit volume of adsorbent column (mg/L), V = linear flow velocity of influent solution (cm/min) and t = service time of column under above conditions (min). The linear flow velocity of feed to bed is calculated by dividing the flow rate (mL/min) by the column section area (cm^2). This equation enables the service time, t, of an adsorption bed to be

determined for a specified bed depth (h) which is correlated with the process parameter such as initial influent concentration, flow rate and adsorption capacity.

BDST model ignores the intra-particle mass transfer resistance and the external film resistance such that the adsorbate is adsorbed onto the adsorbent surface directly. This model also considers the adsorption capacity to be constant throughout the bed when the adsorption zone is moving at constant speed along the column.

Equation (5.13) enables the service time t, of an adsorption bed to be determined for a specified bed depth, h, of the adsorbent. The second term on the right hand side of the Equation (5.13) represents the time required for the effluent fluoride to establish its breakthrough curve; that is, it represents that part of the bed which is not saturated when the fluoride concentration in the solution leaving the bed is above the breakthrough value of C_e. The BDST model can predict service time versus bed depth according to the desired percentage breakthrough value and can measure the capacity of the bed at various percentage breakthrough values (Ko et al. 2000).

The critical bed depth (h_o) is the theoretical depth of adsorbent sufficient to prevent the adsorbate concentration from exceeding breakthrough concentration at t=0 when concentration $C_t = C_B$, where C_B = concentration at the breakthrough. In other words h_o is the critical bed depth (in cm) of the adsorbent of column sufficient to ensure that the outlet solute concentration does not exceed the breakthrough concentration (C_B) at time t=0. h_o is obtained from Equation (5.14) (Ghorai & Pant 2005). By applying the experimental data to this equation critical bed depth was determined for turmeric powder at fixed conditions.

$$h_0 = \frac{V}{k_a N_0} ln\left(\frac{C_0}{C_B} - 1\right) \qquad (5.14)$$

5.2.3 Bohart-Adams model

Bohart-Adams model has been originally established to explain the fundamental relationship between C_t/C_o and t in a gas-charcoal adsorption system (Bohart and Adams 1920) which is widely applied today to explain adsorption behaviour in natural adsorption systems. This model assumes that adsorption is proportional to both the residual capacity of the adsorbent as well as the adsorbate concentration. This model is equal to BDST model

but it is often used to describe the initial part of the breakthrough curves showing where there is a higher slope. It is expressed by Equation (5.15).

$$\ln\left[\frac{C_t}{C_o}\right] = k_{AB}C_o \times \mathrm{t} - \frac{k_{AB}N_o h}{v} \qquad (5.15)$$

Where k_{AB} = kinetic constant (mL/mg/min), V is the linear velocity (flow rate/column section area, cm/min). A linear plot of ln (C_t/C_o) against time (t) was drawn and values of k_{AB} and N_o were determined from the slope and interception of the plot, respectively.

5.2.4 Thomas Model

Thomas model assumes Langmuir kinetics of adsorption-desorption on the assumption that the rate of driving force obeys second-order reversible reaction kinetics (Thomas 1944). Thomas model was applied to explain the adsorption of fluoride in a column with regards to kinetics of column adsorption. The linearized form of the Thomas model can be expressed in Equation (5.16) (Ahmad and Hameed 2010).

$$\ln\left[\frac{C_0}{C_t} - 1\right] = \frac{k_{TH}q_e W}{Q} - k_{TH}C_0 t \qquad (5.16)$$

where k_{TH} = Thomas rate constant (mL/min.mg), Q = inlet flow rate (mL/min), q_e = sorption capacity of the adsorbent per unit mass of the adsorbent (mg/g), and W = mass of adsorbent (g).

The experimental data $\ln\left[\frac{C_0}{C_B} - 1\right]$ was plotted against time t to find out k_{TH}.

5.2.5 Column regeneration

Turmeric was regenerated using 0.1M and 0.5M NaOH solutions to find out whether it can be used in further adsorption cycles. Columns with a bed of 0.75 g turmeric were subjected to adsorption test with 3.09 mg/L fluoride solution. It was flushed with 0.1M and 0.5M NaOH solutions. Then the regenerated columns were used for another cycle of adsorption using fluoride solutions of same concentration (3.09 mg/L). In the second cycle again the adsorption capacity was determined by each column that was regenerated. All the regeneration studies were carried out at a flow rate of 0.33 mL/min by keeping the other parameters constant.

5.3 Summary

The selection criteria of natural material for fluoride were explained in this chapter. The natural materials were namely turmeric rhizome powder (*Curcuma longa*), ginger rhizome powder (*Zingiber officinale*) and powdered curry leaves (*Murraya koenigii*). The main criteria for selection of these materials were cheap and local availability. These are also used in Sri Lanka as spices. Out of them Turmeric is known to have medicinal values and are being used as a water purifying material in India and Sri Lanka. The standard methods used to process these natural materials were explained. The experimental procedures followed to identify the best suitable adsorbent material were described. The laboratory procedures followed for batch and column experiments with turmeric to remove fluoride were explained. Thermodynamic and kinetic models were also described which were applied for experimental results. Breakthrough analysis, bed depth service time (BDST) model, Bohart-Adams model and Thomas model were explained to identify fluoride adsorption characteristics using turmeric powder in water. Finally column regeneration procedure was explained which was useful in reuse of adsorbent in subsequent cycles.

6 RESULTS AND DISCUSSIONS – STATISTICAL ANALYSIS ON WATER SAMPLING

Patient and non-patient samples were grouped as ANU-P (Anuradhapura patients), ANU-NP (Anuradhapura non-patients), POL-P (Polonnaruwa patients), POL-NP (Polonnaruwa non-patients) and GAM-C (Gampaha control) in the statistical analysis of this research. A secondary data set collected by Chandrajith et al. (2011a), was also analysed in this research separately. All water parameter values were compared with WHO standards in order to identify the contaminant tolerable levels. ANOVA with Dunnett's T3 post-hoc tests and Kruskal Wallis (KW) with Mann-Whitney's post-hoc tests were used to differentiate water parameters based on mean and median values, respectively. Group significance of each test was determined at $p < 0.05$ (95% confidence level). The null hypotheses (H_o) for ANOVA and Kruskal Wallis tests were that mean and median values respectively of a variable in each sampling group were significantly different. Factorial Analysis (FA) was applied to identify the association of different chemical parameters to form factor combinations. Discriminant Analysis (DA) was applied to indicate how much of the original classifications of ANU-P, ANU-NP, POL-P, POL-NP and GAM-C samples were correctly classified. All these statistical methods were applied for both primary and secondary data sets using SPSS software available at RMIT. The results were interpreted in relation to hydrogeology of the region. Soil sample results of the CKD endemic areas, sodium to calcium ratios, heavy metals and other sources of fluoride in drinking water samples were also discussed in this chapter.

6.1 Comparison with WHO standards

The mean, median, maximum and minimum values of the water quality parameters obtained in different sampling groups are presented in Table 6.1.The extent of variations of parameters in each sampling groups are shown by box plots in Figure 6.1. Mean and median values of chemical parameters namely chloride (Cl^-), fluoride (F^-), nitrate (NO_3^-), phosphate (PO_4^{3-}), calcium (Ca^{2+}), magnesium (Mg^{2+}**)** and sodium (Na^+) in all the sampling groups did not exceed the WHO standards as shown in Table 6.1. However some individual samples have exceeded the WHO limits in Cl^-, F^-, NO_3^-, Ca^{2+} and Na^+ in Anuradhapura patients and non-patients (e.g. Cl^- 11.75%, F^- 3.92%, NO_3^- 2.94%, Ca^{2+} 1.96% and Na^+ 5.88%). On the other

hand, a few NO_3^- values have exceeded WHO limits in the Polonnaruwa patients. PO_4^{3-} and Mg^{2+} values have not exceeded WHO limits in patients and non-patients in Anuradhapura and Polonnaruwa as well as in Gampaha control area samples.

Table 6.1 Descriptive statistics of different sampling groups

Group	Descriptive statistics	Cl^- (mg/L)	F^- (mg/L)	NO_3^- (mg/L)	PO_4^{3-} (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)
ANU-P	Mean	81.71	0.52	1.14	0.18	61.26	27.82	78.78
	Median	34.25	0.42	0.10	0.15	48.78	24.69	68.24
	Max	519.00	1.75	17.75	1.06	207.82	76.30	392.50
	Min	4.00	0.00	0.00	0.04	0.41	0.20	0.50
POL-P	Mean	48.75	0.49	1.89	0.44	69.43	28.65	40.17
	Median	29.19	0.46	0.17	0.11	70.96	25.55	35.81
	Max	167.70	1.14	23.48	2.85	120.27	77.34	89.01
	Min	10.00	0.04	0.03	0.03	24.37	5.27	9.90
ANU-NP	Mean	112.87	0.39	3.73	0.18	66.81	31.01	79.17
	Median	99.28	0.43	1.32	0.14	61.03	27.96	84.11
	Max	442.00	1.08	15.77	0.52	180.47	85.79	163.83
	Min	17.00	0.02	0.02	0.02	24.30	6.20	19.00
POL-NP	Mean	30.51	0.48	0.17	0.08	60.31	22.03	33.60
	Median	25.40	0.43	0.08	0.04	61.95	19.12	31.81
	Max	95.46	1.16	0.80	0.59	100.04	57.73	86.43
	Min	1.86	0.02	0.02	0.02	24.83	0.85	2.34
GAM-C	Mean	36.50	0.00	7.25	0.02	10.57	1.71	25.95
	Median	36.00	0.00	7.34	0.01	9.70	1.55	23.80
	Max	110.00	0.00	18.27	0.09	27.10	3.10	84.90
	Min	6.00	0.00	1.80	0.01	2.40	0.80	3.80
WHO Standard		250	1.5	10	5	200	150	200

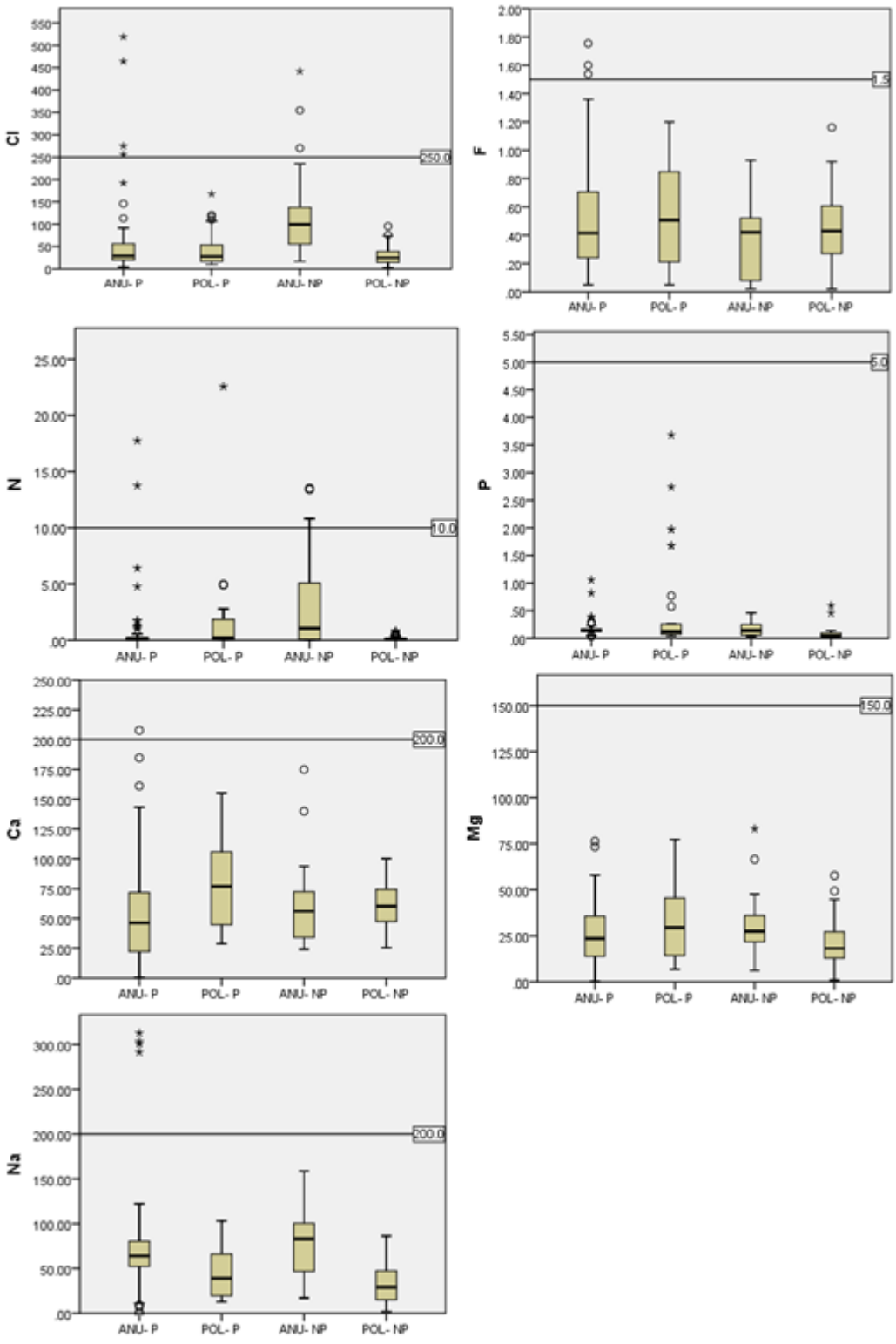


Figure 6.1 Box plots showing variation of parameters in sampling groups

Note: the following abbreviations are as follows: Cl: chloride (Cl^-), F: fluoride (F^-), N: nitrate (NO_3^-), P: phosphate (PO_4^{3-}), Ca: calcium (Ca^{2+}), Mg: magnesium (Mg^{2+}), Na: sodium (Na^+).

Phosphates (PO_4^{3-}) are derived from leaching of phosphorus rich bedrocks, human wastes, industrial wastes (which are not present in the area), decomposing organic matter and fertilizer uses. Because of agricultural land use pattern, the CKD endemic areas are subjected to phosphate fertilizer applications. However movement of soluble phosphorous to groundwater can be limited due to fixation of phosphates by soil minerals (Wijewardena 1998).

Nitrate levels have exceeded WHO standards in 2.94% samples of Anuradhapura patients, in 20% samples of Anuradhapura non-patients and 21.43% samples in Gampaha. Nitrate in groundwater in the CKD endemic areas can be derived from many sources such as mineralization of soils, organic matters, symbiotic nitrogen fixations, fertilizers, animal wastes and green manure. Ammonium fertilizer applied in agriculture is a good source of nitrogen in groundwater (Nagarajah et al. 1988). Nitrates are extremely soluble in water and can easily move through soil into drinking water sources (Saba et al. 2006). Nitrate itself is not considered toxic, but after consumption, bacteria in upper gastro-intestinal tract cause nitrate (NO_3^-) to reduce into nitrite (NO_2^-), which in turn is absorbed to the bloodstream. High level of NO_2^- is found to cause gastric cancer (Olsen 1978), but there is no evidence available of CKD by NO_2^-.

In Anuradhapura patient areas, F^- levels in 3.92% of the drinking water samples have exceeded the WHO maximum permissible limit (MPL) of 1.5 mg/L, while this limit has not exceeded in Polonnaruwa patient and non-patient samples. With regard to the limit of 0.6 mg/L fluoride, 29.41% and 21.67% samples in Anuradhapura patients and non-patients respectively, and 35.56% and 25% samples in Polonnaruwa patients and non-patients respectively, have exceeded the limit. Fluoride levels in Anuradhapura patients were in a wider range than Polonnaruwa patients. Median value of fluoride in Anuradhapura patients was lower than Polonnaruwa patients, however in Anuradhapura patients, fluoride levels in the third quartile and above were in a broader range than in all the other sampling groups.

Chloride levels in Polonnaruwa patients and non-patients have not exceeded the WHO recommended limit of 250 mg/L, whereas 11.75% and 5% of samples from Anuradhapura patients and non-patients respectively have exceeded this limit. As shown in box plots, the spread and median values of Cl^- in Anuradhapura patients and non-patients were higher

than Polonnaruwa patients and non-patients. However there is no known link between elevated chloride concentrations and CKD incidences.

The maximum recommended level of sodium by WHO (200 mg/L) have been exceeded in 5.88% of Anuradhapura patients samples whereas other sampling groups have not exceeded this limit. Calcium level of WHO limit (200 mg/L) has exceeded in 1.96% of Anuradhapura patient samples whereas other sampling groups have not exceeded this limit.

6.2 Statistical significance tests for different sampling groups

Univariate Analysis of Variance (ANOVA) and Dunnett's T3 test results on mean values of different sampling groups are presented in Table 6.2. ANOVA results showed group differences as a whole to be significant (category significance) in Cl^-, NO_3^-, PO_4^{3-}, Mg^{2+} and Na^+ at $p < 0.05$. Dunnett's T3 test results showed which pairs of groups were significantly different at $p < 0.05$. In this analysis it was observed that CKD endemic area samples have similar variances but Gampaha control area samples have a different variance with other samples. Therefore Gampaha samples were not included in ANOVA and Dunnett's T3 post-hoc test.

Parameters of Cl^-, PO_4^{3-} and Na^+ were significantly different between Anuradhapura and Polonnaruwa patient groups. Fluoride was significantly different between Anuradhapura patient and non-patient groups, however it was not significantly different for any other groups including Polonnaruwa patient and non-patient groups.

Magnesium was significantly different between Anuradhapura patient and Polonnaruwa non-patient groups, between Polonnaruwa patient and non-patient groups, and between Anuradhapura and Polonnaruwa non-patient groups. On the other hand, sodium was not significantly different between patient and non-patient sampling groups of both Anuradhapura and Polonnaruwa. Chloride was significantly different between all pairs except Anuradhapura patients and non-patients. Phosphate also was not significantly different between Anuradhapura patient and non-patient sampling groups but it was significantly different between all the other pairs of groups. Calcium was not significantly different in any of the six pairs of groups. Nitrate was not significantly different in

Anuradhapura and Polonnaruwa patient groups and in Anuradhapura non-patient and Polonnaruwa patient groups.

Table 6.2 ANOVA test with Dunnett's T3 post-hoc test results (*p*-values)

Variable	ANOVA test results (group significance)	Dunnett's T3 test results (for each pair of groups)					
		ANU-P & POL-P	ANU-P & ANU-NP	ANU-P & POL-NP	ANU-NP & POL-P	POL-P & POL-NP	ANU-NP & POL-NP
Cl^-	.000	.011	.061	.000	.000	.003	.000
F^-	.060	.925	.027	.797	.251	1.000	.344
NO_3^-	.000	.762	.005	.000	.160	.008	.000
PO_4^{3-}	.000	.008	1.000	.000	.007	.000	.000
Ca^{2+}	.279	.404	.921	1.000	1.000	.103	.816
Mg^{2+}	.010	1.000	.808	.021	.949	.042	.027
Na^+	.000	.000	.998	.000	.000	.289	.000

(Significance determined at $p < 0.05$)

Kruskal-Wallis and Mann-Whitney's tests results on median values of different sampling groups are given in Table 6.3 with $p < 0.05$ (category significance) in all the parameters except F^-. Mann-Whitney's test results showed which pair of groups was significantly different at $p < 0.05$. Gampaha control area samples were not included in Kruskal Wallis (KW) and Mann-Whitney's post-hoc tests to keep similarity with ANOVA and Dunnett's T3 post-hoc tests.

In this analysis, NO_3^-, PO_4^{3-}, Ca^{2+} and Na^+ were significantly different between Anuradhapura patients and Polonnaruwa patients. Chloride, F^- and NO_3^- were significantly different between Anuradhapura patients and non-patients. Fluoride and Na^+ were not significantly different between Polonnaruwa patients and non-patients. Magnesium showed similar grouping results as shown in Table 6.3.

When the results of ANOVA and Kruskal-Wallis test were compared both of them showed that group differences as a whole in F^- was not significantly different. However among the six sampling group pairs, significant differences in F^- were identified between Anuradhapura patients and non-patients, and between Polonnaruwa patients and Anuradhapura non-patients (significant difference was marginal at $p = 0.048$ in Mann-Whitney's test).

Table 6.3 Kruskal-Wallis (KW) test with Mann-Whitney's post-hoc test results (*p*-values)

Variable	Kruskal-Wallis test results (group significance)	Mann-Whitney's test results (for each pair of groups)					
		ANU-P & POL-P	ANU-P & ANU-NP	ANU-P & POL-NP	ANU-NP & POL-P	POL-P & POL-NP	ANU-NP & POL-NP
Cl^-	.000	.231	.000	.000	.000	.018	.000
F^-	.201	.693	.036	.896	.048	.942	.155
NO_3^-	.000	.000	.000	.945	.008	.000	.000
PO_4^{3-}	.000	.037	.485	.000	.602	.000	.000
Ca^{2+}	.003	.001	.111	.018	.158	.039	.977
Mg^{2+}	.045	.881	.425	.019	.611	.042	.010
Na^+	.000	.000	.100	.000	.000	.085	.000

(Significance determined at $p < 0.05$)

Table 6.1 shows that the mean value of F^- was higher in Anuradhapura patients than all other sampling groups. Contrarily median value of F^- was lower in Anuradhapura patients than all other sampling groups. Although Ca^{2+} mean values were not significantly different among the sampling groups in Table 6.2, the median values showed significant differences among few groups in Table 6.3. Mann-Whitney's test results showed that median values in Ca^{2+} were significantly different between patients of Anuradhapura and Polonnaruwa, between Anuradhapura patients and Polonnaruwa non-patients as well as between patients and non-patients of Polonnaruwa. This fact gave an interesting finding that calcium values were significantly different in Anuradhapura and Polonnaruwa, with respect to patients and non-patients which have not been identified in Dunnett's T3 test in Table 6.2. As such both ANOVA with Dunnett's T3 post-hoc tests and Kruskal-Wallis with Mann-Whitney's post-hoc tests were important in the analysis of water quality parameters, which may give different traits of explanation in relation to data mean and median values. In order to compare these two sets of results easily, a superimposed table (Table 6.4) and a figure (Figure 6.2) was prepared based on chemical ions mean and median results.

Table 6.4 Superimposed results from ANOVA with Dunnett's T3 post-hoc test and Kruskal-Wallis (KW) with Mann-Whitney's post-hoc tests

Variable	Kruskal-Wallis test results	Mann-Whitney's test results (for each pair of groups)					
		ANU-P & POL-P	ANU-P & ANU-NP	ANU-P & POL-NP	ANU-NP & POL-P	POL-P & POL-NP	ANU-NP & POL-NP
Cl^-	Dif	Dif-nDif	nDif -dif	Dif	Dif	Dif	Dif
F^-	nDif	nDif	Dif	nDif	nDif-dif	nDif	nDif
NO_3^-	Dif	nDif-dif	Dif	Dif-nDif	nDif-dif	Dif	Dif
PO_4^{3-}	Dif	Dif	nDif	Dif	Dif-sam	Dif	Dif
Ca^{2+}	nDif-dif	nDif-dif	nDif	nDif-dif	nDif	nDif-dif	nDif
Mg^{2+}	Dif	nDif	nDif	Dif	nDif	Dif	Dif
Na^+	Dif	Dif	nDif	Dif	Dif	nDif	Dif

Note: Dif-nDif = significantly different in mean value test but significantly not different in median value test; nDif-dif = significantly not different in mean value test but significantly different in median value test; Dif = significantly different in both mean value and median value tests; nDif = significantly not different in both mean value and median value tests.

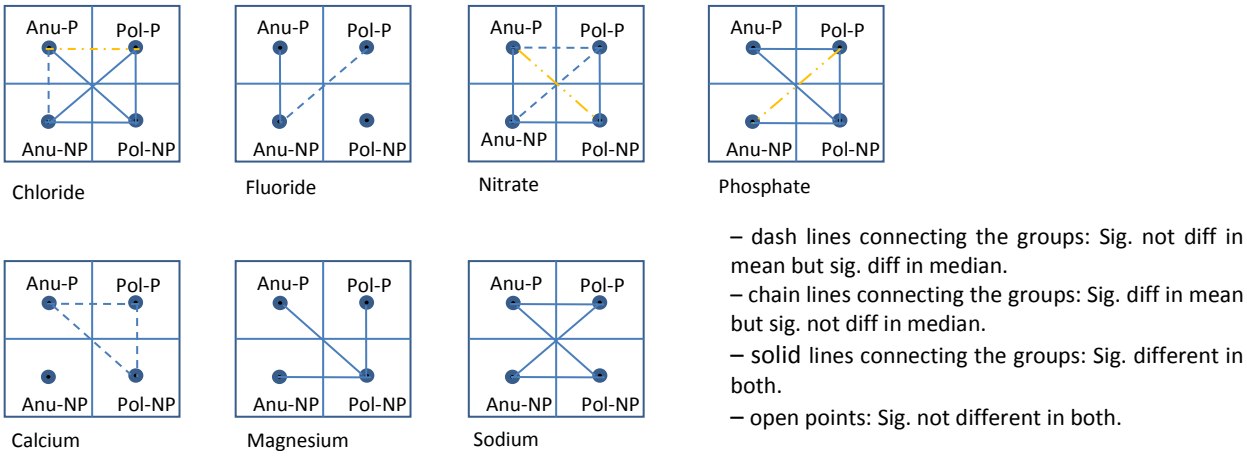


Figure 6.2 Graphical representation of significant differences among the sampling groups for easy delineation

6.3 Factorial Analysis (FA) for identifying chemical combinations

Factorial Analysis (FA) was applied to explain the variables (water parameters) which go together within a group to form factors. Kaiser-Meyer-Olin (KMO) and Bartlett's test for sampling adequacy showed that Anuradhapura patients, Polonnaruwa patients, Anuradhapura non-patients and Polonnaruwa non-patients have values of 0.699, 0.543, 0.552 and 0.770 respectively (shown in Table 6.5) indicating sample adequacies at $p < 0.05$. On the other hand, control area Gamapha had a KMO and Bartlett's test value of 0.482,

which is lower than unacceptable limiting value of 0.5. However Gampaha control area samples were deemed as adequate as the group adequacy value was significant at $p < 0.05$.

Table 6.5 KMO and Bartlett's test of sampling adequacy

Sampling Group	KMO and Bartlett's Test	Significance
ANU- P	0.699	0.00
POL- P	0.543	0.00
ANU-NP	0.552	0.00
POL-NP	0.77	0.00
GAM- C	0.482	0.00

As a first step of FA, cross-correlation matrices were obtained to show whether there were any relations existing between the variables in each group (shown in Annexures 1 to 7). When correlations were above 0.50 and significant at $p < 0.05$, FA was preceded. Scree plot showed how many factors could be extracted from each sampling group having initial Eigen values (IEV) > 1 (Figure 6.3) and Annexures 1 to 7). Component Matrices gave the variables falling within each factor before rotation and Rotated Component Matrices gave the variables falling under each factor after factor rotation (Annexures 1 to 7).

Rotated Factor results for each sampling group were summarised and given in Table 6.6. It gave coefficients of each variable after factor rotations, which were obtained in Rotated Component Matrices. Generally factor loadings in Rotated Component Matrices having values below 0.4 are suppressed. When a variable falls into two factors in a Rotated Component Matrix, the factor where it has a higher value is considered as its original factor. For example in Anuradhapura non-patients, Na^+ loads high on both Factor 1 and Factor 2, however it loads higher on Factor 2, therefore Na^+ is considered under Factor 2. Component Transformation Matrix is produced by un-rotated matrix divided by rotated matrix. Component plot in rotated space was given to explain the factor results graphically using Component Transformation Matrix values. The coordinates in the factor matrix are the factor loadings for the rotated solution. If the factor solution has more than 2 factors it gave a three dimensional plot. Factor matrices for each sampling group are given in Figure 6.4 (also Annexures 1 to 7).

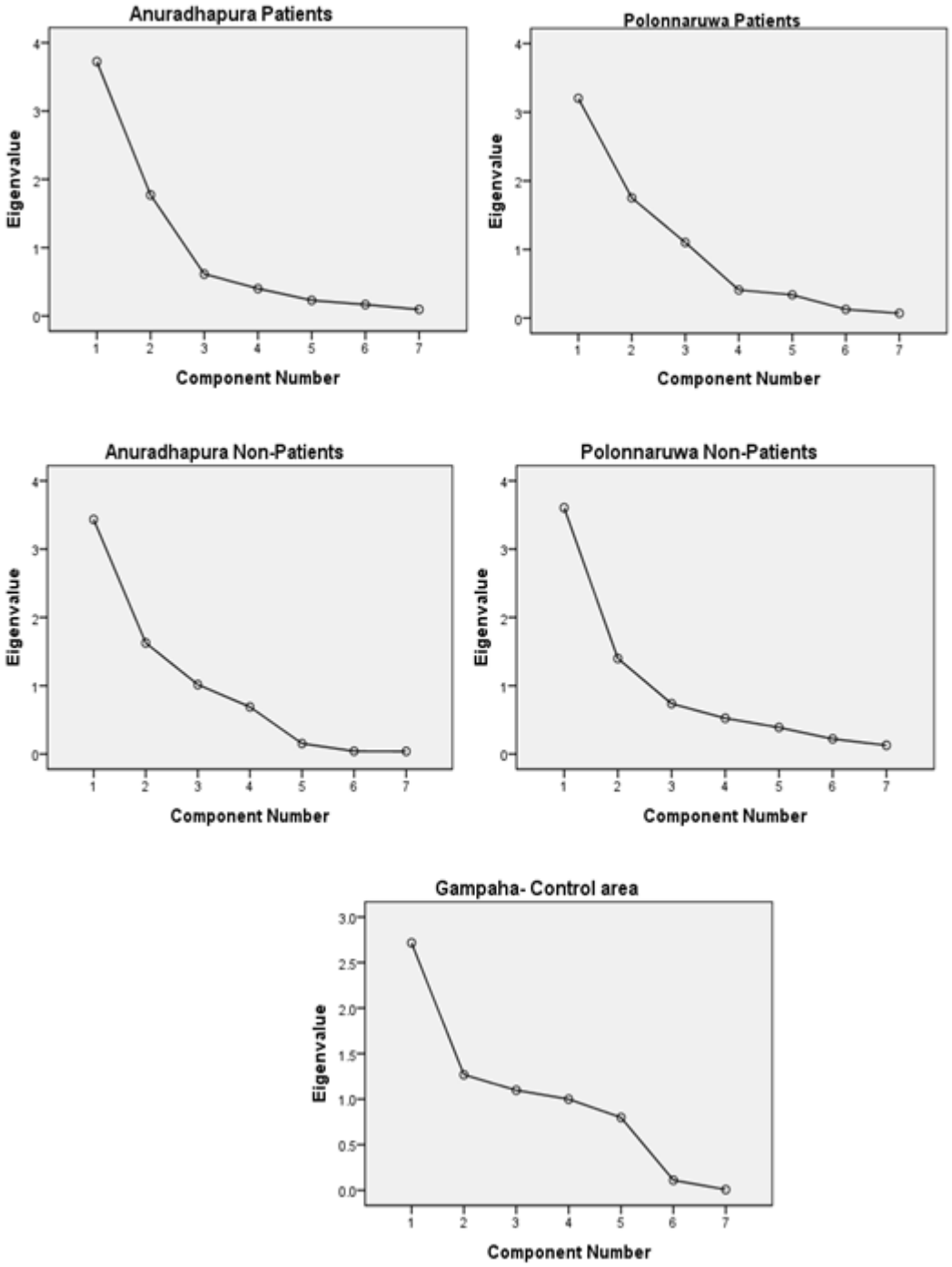


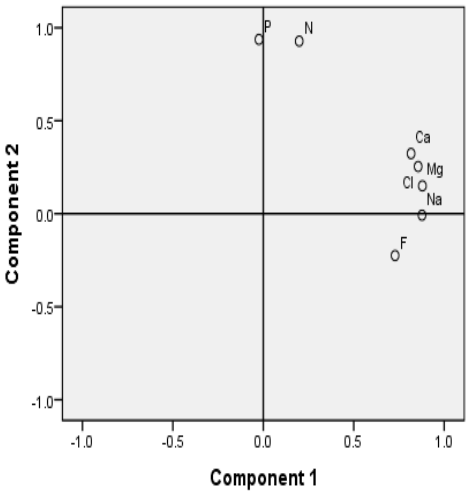
Figure 6.3 Screen plots showing the Eigen values corresponding to Factors

Table 6.6 Rotated component matrix results for each sampling group showing factor loadings

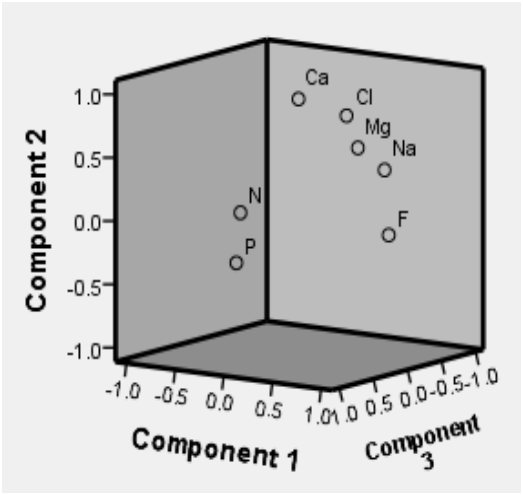
Sampling group	Component / factor	Variables in each component / factor	Coefficients of variables after factor rotation						
			Cl^-	F^-	NO_3^-	PO_4^{3-}	Ca^{2+}	Mg^{2+}	Na^+
ANU-P	1	Cl^-, F^-, Ca^{2+}, Mg^{2+}, Na^+	0.868	0.752			0.82	0.887	0.886
	2	NO_3^-, PO_4^{3-}			0.929	0.939			
POL-P	1	F^-, Mg^{2+}, Na^+		0.93				0.708	0.862
	2	Cl^-, Ca^{2+}	0.797				0.922		
	3	NO_3^-, PO_4^{3-}			0.942	0.903			
ANU-NP	1	Cl^-, Ca^{2+}, Mg^{2+}, Na^+	0.929				0.929	0.957	0.619
	2	NO_3^-, PO_4^{3-}, Na^+			0.771	-0.61			-0.764
	3	F^-		0.96					
POL-NP	1	Cl^-, F^-, Ca^{2+}, Mg^{2+}, Na^+	0.725	0.885			0.769	0.934	0.827
	2	NO_3^-, PO_4^{3-}			0.858	0.729			
GAM-C	1	Cl^-, Na^+	0.979						0.978
	2	NO_3^-, Ca^{2+}, Mg^{2+}			0.717		-0.72	0.723	
	3	PO_4^{3-}				0.921			

The FA results are summarised in Table 6.7. The steps followed to obtain the final results of FA are shown in Annexures 1 to 7. According to results Anuradhapura patient samples were grouped into two factors with the first factor having the highest initial Eigen value of 3.78 and a percentage variance of 54%. Numbers of factors extracted from other groups were: 3 factors for Polonnaruwa patients, 3 factors for Anuradhapura non-patients, 2 factors for Polonnaruwa non-patients and 3 factors for Gampaha. When Anuradhapura patients, Polonnaruwa patients and Polonnaruwa non-patients were compared, F^-, Na^+ and Mg^{2+} were found as a common factor in all the three groups having significantly high initial Eigen values and percentage variances. Anuradhapura non-patient samples were different from other three groups as F^- did not combine with any other variables to form a factor in that group.

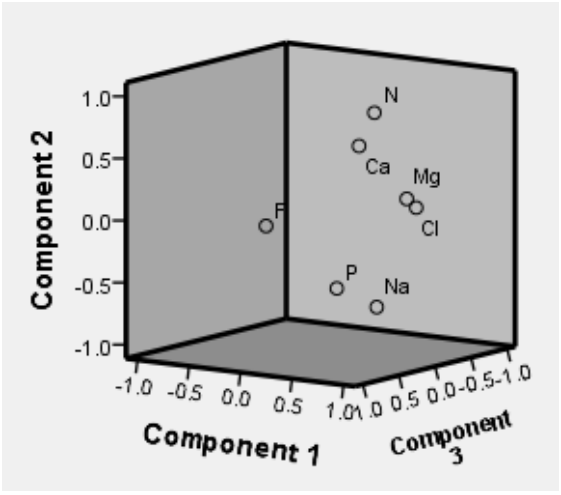
Anuradhapura Patients



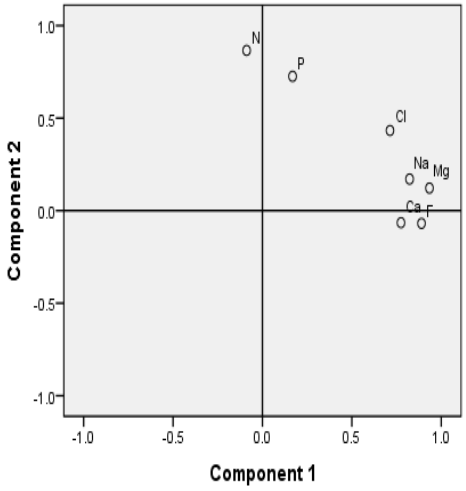
Polonnaruwa Patients



Anuradhapura Non-Patients



Polonnaruwa Non-Patients



Control- Gampaha

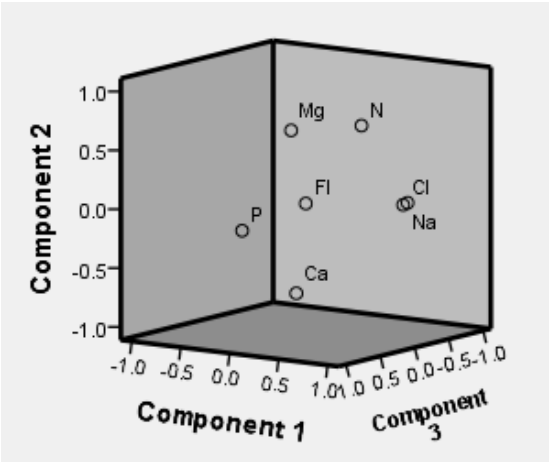


Figure 6.4 The rotated factor matrices for sampling groups

Table 6.7 Summary of the Factorial Analysis (FA) results

Sampling Group	Factors	Initial Eigen Value	% variance	Variables	Cronbach's Alpha based on Standardized Items
ANU-P	1	3.78	54.00	Cl^-, F^-, Ca^{2+}, Mg^{2+}, Na^+	.903
	2	1.78	25.43	NO_3^-, PO_4^{3-}	.890
POL-P	1	3.18	45.48	F^-, Mg^{2+}, Na^+	.871
	2	1.78	25.42	Cl^-, Ca^{2+}	.775
	3	1.11	15.93	NO_3^-, PO_4^{3-}	.834
ANU-NP	1	3.27	46.76	Cl^-, Ca^{2+}, Mg^{2+}	.673
	2	1.59	22.85	NO_3^-, PO_4^{3-}, Na^+	.002
	3	1.04	14.86	F^-	-
POL-NP	1	3.58	51.15	Cl^-, F^-, Ca^{2+}, Mg^{2+}, Na^+	.892
	2	1.40	20.04	NO_3^-, PO_4^{3-}	.494
GAM-C	1	2.71	38.79	Cl^-, Na^+	.995
	2	1.29	18.12	NO_3^-, Ca^{2+}, Mg^{2+}	.221
	3	1.09	15.69	PO_4^{3-}	-

After factor extraction, reliability analysis was carried to see reliability of variables in each factor (Table 6.8). As explained in methodology, Cronbach's Alpha was used to determine the reliability of each factor. In Anuradhapura patients the first Factor was reliable with a Cronbach's alpha value of 0.903 comprised with variables of Cl^-, F^-, Ca^{2+}, Mg^{2+} and Na^{2+}. When Mg^{2+} and Na^+ were eliminated from this Factor, Cronbach's alpha value dropped from 0.903 to 0.742 and 0.594 respectively, indicating that both the variables were good indicators of this Factor. However Na^+ was more reliable than Mg^2 in this factor as reliability dropped more when Na^+ was eliminated compared to elimination of Mg^{2+}. As such, Na^+ and F^- together made a more reliable chemical combination in Anuradhapura patients than Mg^{2+} and F^-combination. When Ca^{2+} and Cl^- were eliminated from this Factor, Cronbach's Alpha value went down to 0.647 and 0.660 respectively; however these chemical ions have no significance in CKD. In Polonnaruwa patients the first Factor made of F^-, Na^+ and Mg^{2+} was reliable with a Cronbach's Alpha value of .871. When Na^+ and Mg^{2+} were eliminated from this factor, reliability of the factor dropped significantly to a Cronbach's alpha of 0.037 and 0.035 respectively, which means both these variables were reliable in explaining the given Factor. As such Na^+ and F^- as well as Mg^{2+} and F^- were both reliable chemical combinations that had formed in Polonnaruwa patient samples.

Table 6.8 Reliability analysis results shown by Cronbach's Alpha value

Group	Variables	Cronbach's Alpha value (from Table 6)	Cronbach's Alpha if Item deleted				
			Cl^-	F^-	Ca^{2+}	Mg^{2+}	Na^+
ANU-P	Cl^-, F^-, Ca^{2+}, Mg^{2+}, Na^+	.903	.660	.803	.647	.742	.594
POL-P	F^-, Mg^{2+}, Na^+	.871	-	.889	-	.035	.037
POL-NP	Cl^-, F^-, Ca^{2+}, Mg^{2+}, Na^+	.892	.708	.836	.748	.677	.705

Polonnaruwa non-patient samples consisted of variables Cl^-, F^-, Ca^{2+}, Mg^{2+} and Na^{2+}. When Mg^{2+} and Na^+ were deleted from Polonnaruwa non-patients the original Cronbach's Alpha value reduced from 0.892 to 0.677 and 0.705 respectively, indicating Mg^{2+} was more reliable than Na^+ to combine with F^-. Therefore, it was concluded that Na^+ and F^- combination was secondary to $Mg^{2+}$and F^- combination in Polonnaruwa non-patients.

Anuradhapura non-patient samples were different from other three groups as F^- did not combine with any other variables to form a Factor. As a result reliability test was not possible. Also Mg^{2+} and Na^+ belonged to two different Factors. When Gampaha control area was considered, F^- was not detected in water samples and therefore Na^+ and F^- combining in FA could not be identified.

Chloride was more reliable compared to F^- in joining the first Factors in Anuradhapura patients and Polonnaruwa non-patients according to reliability values given in Table 6.8. This meant that there were more tendencies to form Cl^- in water than F^- with Na^+, Mg^{2+} and Ca^{2+} in these two groups. However complexion of F^- was the concern which needed to be investigated in this analysis.

According to FA it can be concluded that variables of Na^+ and F^- going together having a significant reliability value is a feature that was identified in both Anuradhapura patients and Polonnaruwa patients to form sodium fluoride (NaF). With regard to non-patient and control samples Na^+ and F^- combination was less reliable or absent and Mg^{2+} and F^- were the ions that combined to form factors. Sodium and F^- going in one factor could not be identified in Gampaha control area samples.

In summary, therefore, it was concluded that Na^+ and F^- combination was the most evident combination that could be identified in both Anuradhapura and Polonnaruwa patient samples which was not reliable in Anuradhapura and Polonnaruwa non-patient samples. In Polonnaruwa patient water, Na^+ and F^- combination was more reliably distinguishable than in Polonnaruwa non-patient water, whereas Mg^{2+} and F^- combination was more evident in Polonnaruwa non-patient water. Sodium and F^- combination was prominent in Anuradhapura patients compared to Polonnaruwa patients as Mg^{2+} and F^- combination was equally significant to Na^+ and F^- combination in Polonnaruwa patients. With that it is worthwhile to mention that in NCP, almost three times more CKD patients and deaths are reported in Anuradhapura than in Polonnaruwa (Poulter & Mendis 2009).

The combination of Na^+ and F^- could make NaF which is a risk factor of CKD whereas Mg^{2+} and F^- combination to form MgF_2 is not known for any risk to CKD. The possible combination between Ca^{2+} and F^- to form CaF_2 is also not known as a CKD hazard. This can be explained with the geology in the area where F^- concentration in groundwater can be explained by higher solubility of sodium fluoride (NaF) compared to MgF_2 or CaF_2 (Ozsvath 2006).

6.4 Discriminant Analysis (DA)

Discriminant Analysis (DA) was applied to find out how much the group classifications considered were correct with respect to the CKD endemic area's groups of Anuradhapura and Polonnaruwa patients and non-patients. The results given in Table 6.9 showed that in Anuradhapura patient samples, 54.9% data were correctly classified under its own group, yet 16.7, 14.7 and 13.7% of those data were classified under Polonnaruwa patient, Anuradhapura non-patient and Polonnaruwa non-patient groups, respectively. This indicated that more than 50% of the data/samples in this group fell under this group/ category giving correct classification. When Polonnaruwa patient data were considered, less than 50% data fell under its own group, while almost equal percentage of them had similarities to Polonnaruwa non-patient category. This indicated that Polonnaruwa patient samples have somewhat equal affinity to Polonnaruwa non-patient characteristics. In Anuradhapura non-patients 60% data were correctly classified under its own classification while 85% data were correctly classified in Polonnaruwa non-patient groups. As such DA gave a picture of the percentage of samples/data which correctly fell under its own

category. As a whole 58.3% of the original samples were correctly classified within their own groups.

Table 6.9 Sampling classification results based on Discriminant Analysis (DA)

Group	Predicted group membership, %				Total
	ANU- P	POL- P	ANU- NP	POL- NP	
ANU-P	54.9	16.7	14.7	13.7	100
POL- P	11.1	43.3	4.4	41.1	100
ANU-NP	30	0	60	10	100
POL- NP	5	10	0	85	100

Note: 58.3% of the original group samples were correctly classified.

6.5 Comparison between Factorial Analysis and Discriminant Analysis results

When FA results were compared with DA results in Anuradhapura patients samplings, approximately 55% of data which were classified under its own group can be explained having Na^+ and F^- as the primary combination in its water samples. In Anuradhapura non-patients, 60% of the samples can be expected to be free of Na^+ and F^- combination as identified in the FA. In Polonnaruwa non-patients 85% of samples were under its own classification which explained 85% of the data showing a more reliable Mg^+ and F^- combination than Na^+ and F^-. On the other hand, Polonnaruwa patient samplings had almost equal distributions under its own classification (43.3%) and non-patient classification (41.1%), which explained why equally reliable combinations of Na^+ and F^-, and Mg^+ and F^- were obtained.

Therefore Na^+ and $F^-$was the foremost evident combination that could be identified in both Anuradhapura and Polonnaruwa patient samples which was not that apparent in non-patient samples. The combination of Na^+ and F^- could make NaF which is a risk factor of CKD whereas Mg^{2+} and F^- combination to form MgF_2 is not known for any risk to CKD. The possible combination between Ca^{2+} and F^- to form CaF_2 is also not known as a CKD hazard.

6.6 ANOVA, Kruskal-Wallis and post-hoc results comparison with Factorial results

When F^- levels of Anuradhapura and Polonnaruwa patients and non-patients were considered, both ANOVA and Kruskal-Wallis tests showed that significant differences could not be identified between the sampling groups with regard to mean and median values. The post-hoc results of Dunnett's T3 and Mann-Whitney's tests showed that average and median Na^+ values respectively were not significantly different between Anuradhapura patients and non-patients, and Polonnaruwa patients and non-patients, but they were significantly different between Anuradhapura and Polonnaruwa in terms of both patients and non-patients. This indicated that when F^- was not significantly different among the groups, Na^+ made the significant differences in the two districts. Also it was observed that in Anuradhapura patients Na^+ values in some locations have exceeded 200 mg/L (WHO recommended limit) extending up to 300 mg/L, which were seen as outliers in the box plots indicating this group was having relatively high Na^+ values.

As such, the difference between Anuradhapura and Polonnaruwa patient and non-patient groups were that in patient samples F^- and Na^+ combination was prominent which was less significant or non-existent in non-patients. The total statistical procedures gave the conclusion that although ANOVA and Kruskal-Wallis tests helped to identify mean and median differences respectively with their post-hoc results, they were not sufficient to conclude the significant differences between patients and non-patient sampling groups. On the other hand FA was an important analytical tool in this research to identify the correlations in water parameters. This is important in groundwater analysis as ions exist in relation to each other

6.7 Data analysis comparison with secondary data base

The secondary data set collected by Chandrajith et al. (2011a) are analysed here to validate the primary data findings. The mean, median and max-min values of those water chemical ions are shown in Table 6.10. The average and median values of all those chemical ions have not exceeded (except Huruluwewa in Mg^{2+} and Na^+) the maximum permissible limits

recommended by WHO in all the sampling locations as shown in Table 6.10. However some individual samples have exceeded the WHO limits.

The results as shown in Tables 6.11 and 6.12 were obtained from the secondary data applied with ANOVA with Dunnett's T3 post-hoc test and Kruskal-Wallis with Mann-Whitney's post-hoc test, respectively. ANOVA with Dunnett's T3 post-hoc tests were carried for chloride and fluoride only while Kruskal-Wallis with Mann Whitney's post-hoc tests were carried for all the chemical ions considered. ANOVA did not give results for NO_3^-, PO_4^{3-}, Ca^{2+}, Mg^{2+} and Na^+ as total degrees of freedom for dependent variable were too large to be handled by this procedure in each case. The data from Medawachchiya (endemic area) and Wellawaya (non-endemic) could not be analysed due to inadequate sample size.

Unlike to primary data, fluoride mean values from secondary data were significantly different among the locations considered according to ANOVA and Kruskal-Wallis tests at $p < 0.05$ (Tables 6.11 and 6.12). However, Dunnett's T3 and Mann-Whitney's post-hoc tests showed that F^- values were not significantly different for the CKD endemic samples of Girandurukotte and Padaviya when compared with samples of Huruluwewa. Mann-Whitney's post-hoc test results showed that Na^+ was significantly different among all sampling locations. Therefore no clear conclusion could be drawn depending on these differences or non-differences as some CKD endemic samples were significantly different in Na^+ and F^- levels (e.g. Girandurukotte and Nikawewa) whereas in some other CKD non-endemic samples these chemical ions were not significantly different (e.g. Padaviya and Huruluwewa). As such presence or absence of CKD in the areas could not be absolutely concluded with the above analytical processes.

The secondary data were analysed using FA as shown in Table 6.13. Rotated Factor matrices for each sampling group are shown in Figure 6.5. Detailed FA results for Girandurukotte and Huruluwewa are given in Annexures 6-7. FA results of Girandurukotte, Nikawewa and Padaviya CKD endemic area samples were similar to Anuradhapura patient factor results with factors consisting of Na^+ and F^-. However in Nikawewa it was grouped in the third Factor with less reliability. So, with secondary data too it was concluded that the difference was Na^+ and F^- combining in a factor in endemic samples while Mg^{2+} and F^- combining in another factor in non-endemic samples. According to ANOVA and Kruskal-Wallis test results

F^- was significantly different between the groups in mean and median values, respectively. According to Dunnett's T3 and Mann-Whitney's post-hoc tests it was observed that F^- was not significantly different between the CKD endemic samples of Girandurukotte and Padaviya when compared with non-endemic samples of Huruluwewa. However Mann-Whitney's post-hoc test results showed that Na^+ was significantly different between these sampling groups. Therefore, it was apparent that the significant difference in CKD endemic groups and non-endemic groups were due to Na^+ variation rather than F^-.

Table 6.10 Secondary data values of each chemical parameter in different sampling locations

Area	Descriptive statistics	Cl^- (mg/L)	F^- (mg/L)	NO_3^- (mg/L)	PO_4^{3-} (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Na^+ (mg/L)
Girandurukotte	Mean	25.12	0.64	2.77	0.41	13.81	18.98	22.81
	Median	17.88	0.46	1.60	0.35	13.05	9.52	18.30
	Max	104.75	2.14	9.00	1.60	37.10	79.60	108.00
	Min	2.75	0.02	0.10	0.07	1.02	2.26	1.54
Nikawewa	Mean	82.80	1.21	2.55	1.35	40.31	54.56	135.35
	Median	62.75	0.90	2.00	0.40	26.70	40.10	110.00
	Max	281.00	5.30	17.30	8.40	256.00	313.00	540.00
	Min	13.00	0.02	0.10	0.10	2.38	0.98	15.20
Huruluwewa	Mean	144.61	0.72	1.07	0.31	29.60	188.82	561.08
	Median	112.50	0.61	0.70	0.30	28.30	38.37	414.00
	Max	497.50	1.68	3.90	0.65	58.00	1280.0	1910.00
	Min	14.50	0.02	0.10	0.06	3.57	9.63	38.50
Medawachchiya	Mean	-	1.03	6.19	0.36	33.32	98.02	46.50
	Median	-	1.07	0.80	0.38	31.30	19.83	53.80
	Max	-	1.37	25.60	0.61	53.50	785.00	80.70
	Min	-	0.52	0.40	0.14	13.50	11.38	8.02
Padaviya	Mean	174.99	0.62	2.99	0.58	35.03	20.10	58.35
	Median	106.25	0.55	2.10	0.53	26.15	20.60	44.69
	Max	687.50	1.33	9.50	1.74	113.00	41.62	188.11
	Min	27.00	0.02	0.50	0.09	2.35	2.08	2.09
Wellawaya	Mean	216.07	1.05	1.17	0.79	0.53	22.97	48.67
	Median	245.00	1.09	0.90	0.52	0.22	24.80	35.80
	Max	292.50	2.20	2.10	1.96	1.43	30.50	101.00
	Min	92.50	0.45	0.50	0.19	0.04	14.10	19.20
WHO Standard		250	1.5	10	5	200	150	200

The reliability results in Table 6.14 also showed that Na^+ was highly significant and it was more significant than Mg^{2+} in making a factor with F^- in Girandurukotte samples. On the other hand CKD non-endemic samples of Huruluwewa showed that Na^+ and Mg^{2+} were highly and equally significant in making a factor with F^- which was similar to the factor results of Polonnaruwa patient samples. These combinations may have link to the fact of

lesser number of CKD patients in Polonnaruwa endemic area compared to Anuradhapura endemic area. Although Huruluwewa has been identified as a non-patient location by Chandrajith et al. (2011a), it is situated close to CKD areas in NCP of Sri Lanka. As such Na^+ and Mg^{2+} being equally significant in making a combination with F^-, has possibility that the area is in the transition of moving from non-endemic to endemic area. For Nikawewa and Padaviya, reliability test could not be performed as these factors were made of only two variables.

Table 6.11 ANOVA and Dunnett's T3 post-hoc test results on secondary data (*p*-values)

Variable	ANOVA test results (group significance)	Dunnett's T3 post-hoc test results (for each pair of groups)					
		Girandur & Nikawe	Girandur & Padaviya	Girandur & Hurulu	Nikawe & Padaviya	Nikawe & Hurulu	Padaviya & Hurulu
Cl^-	0	0	0	0	0.054	0.07	0.966
F^-	0	0.008	1	0.988	0.004	0.044	0.944

Table 6.12 Kruskal-Wallis test and Mann-Whitney's post-hoc test results on secondary data (*p*-values)

Variable	Kruskal-Wallis test results (group significance)	Mann-Whitney's post-hoc test results (for each pair of groups)					
		Girandur & Nikawe	Girandur & Padaviya	Girandur & Hurulu	Nikawe & Padaviya	Nikawe & Hurulu	Padaviya & Hurulu
Cl^-	.000	.000	.000	.000	.014	.004	.863
F^-	.008	.002	.496	.369	.010	.049	.572
NO_3^-	.002	.885	.430	.004	.270	.004	.000
PO_4^{3-}	.001	.031	.003	.349	.753	.017	.000
Ca^{2+}	.000	.000	.000	.000	.854	.988	.885
Mg^{2+}	.000	.000	.216	.000	.000	.960	.002
Na^+	.000	.000	.000	.000	.000	.000	.000

KMO and Bartlett's test (Table 6.13) of sampling adequacy result did not give results for Wellawaya control samples as the sample size was not adequate. However it was noted that in Wellawaya control area, Na^+ and F^- variables did not combine to form a factor. As such secondary data too indicated that presence of CKD patients in an endemic area was associated with significant Na^+ and F^- combination. The difference between CKD endemic and non-endemic samples were that Na^+ and F^- combined in one Factor in endemic samples, whereas Na^+ and Mg^{2+} equally combined with F^- to form one Factor in non-endemic samples.

Table 6.13 Factor Analysis results summary on secondary data

Sampling group	KMO & Bartlett's test	Sig.	Factor	Initial Eigen value	% variance	Variables	Cronbach's Alpha value
Girandurukot	.661	.00	1	2.50	35.83	F^-, PO_4^{3-}, Mg^{2+}, Na^+	.767
			2	1.24	17.75	NO_3^-, Cl^-	.285
			3	1.01	14.52	Ca^{2+}, Mg^{2+}	.285
Nikawewa	.526	.00	1	2.13	30.52	Cl^-, Mg^{2+}, Ca^{2+}	.612
			2	1.48	21.24	PO_4^{3-}	-
			3	1.23	17.67	F^-, Na^+	.528
Padaviya	.430	.00	1	2.61	37.40	F^-, Na^+	.754
			2	1.47	21.02	Cl^-, Ca^{2+}, PO_4^{3-}	.276
			3	1.09	15.41	Mg^{2+}, NO_3^-	.611
Huruluwewa	.596	.00	1	2.54	36.32	F^-, Mg^{2+}, Na^+	.717
			2	1.37	19.70	Cl^-, NO_3^-, Ca^{2+}	.641
			3	1.01	14.42	PO_4^{3-}	-
Wellawaya	-		1	3.20	45.78	F^-, NO_3^-, PO_4^{3-}	.822
			2	1.38	19.84	Cl^-, Mg^{2+}, Na^+	.771
			3	1.06	15.21	Ca^{2+}	-

Table 6.14 Reliability test using secondary data

Sampling group	Variables	Cronbach's Alpha value if Item deleted					
		F^-	Na^+	Cl^-	Ca^{2+}	Mg^{2+}	PO_4^{3-}
Girandurukotte	F^-, PO_4^{3-}, Mg^{2+}, Na^+	.459	.041	-	-	.071	.471
Huruluwewa	F^-, Mg^{2+}, Na^+	.447	.002	-	-	.002	-

The secondary data were subject to DA and results are given in Table 6.15. The results showed that 93.5% of Girandurukotte samples, 58.8% of Nikawewa samples, 50% of Padaviya samples and 65.5% of Huruluwewa samples could be correctly classified under own groups. More than 50% samples in each sampling category falling under the correct group classification indicated that this proportion of data was correctly classified under each sampling category. Overall 68.1% samples fell under the right classification.

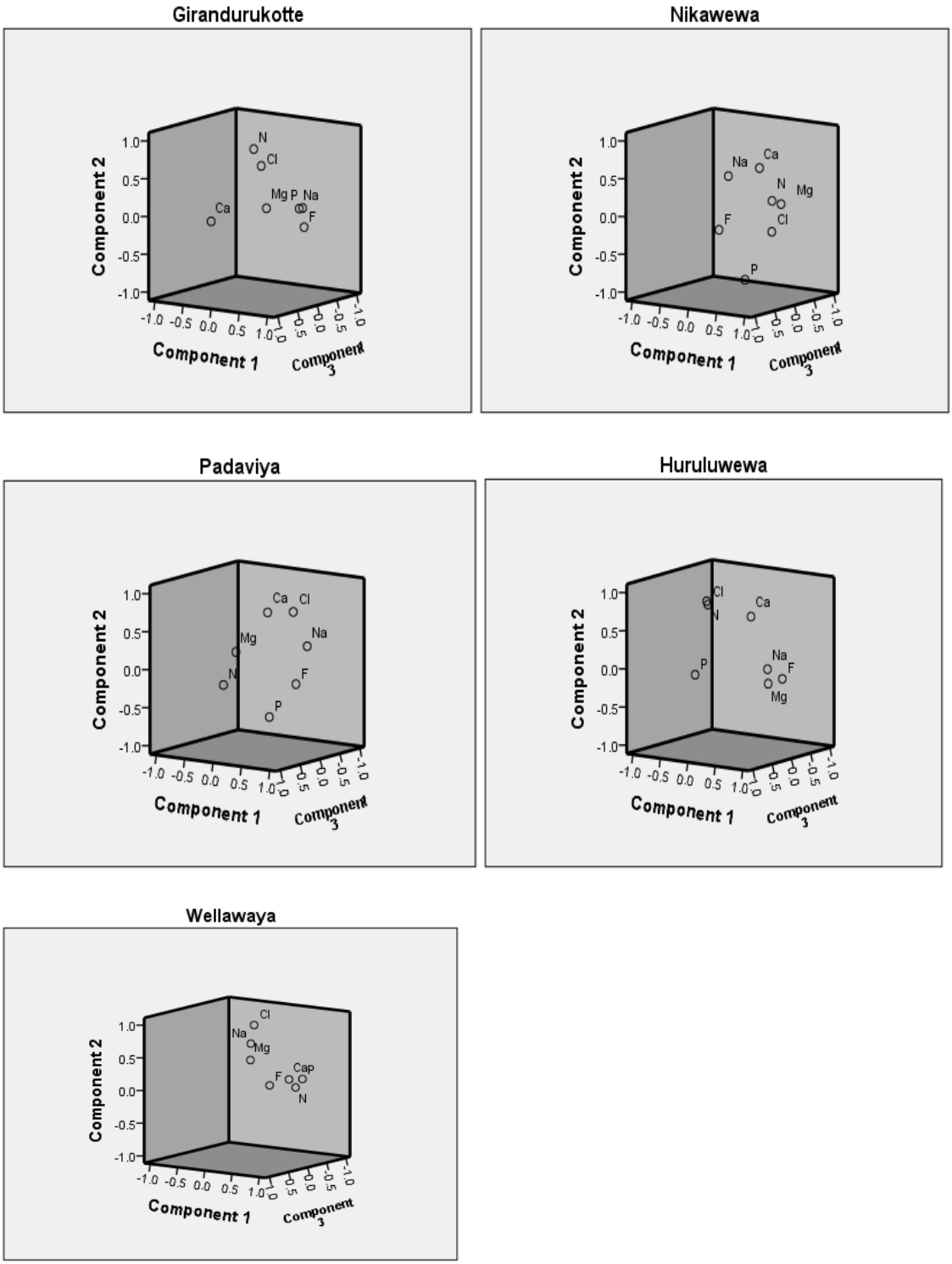


Figure 6.5 The Rotated Factor matrices for sampling groups analysed with secondary data

Table 6.15 Predicted group membership of secondary data based on Discriminant Analysis

Sampling group	Predicted group membership as a %				Total
	Girandurukotte	Nikawewa	Padaviya	Huruluwewa	
Girandurukotte	93.5	4.3	2.2	-	100
Nikawewa	27.5	58.8	9.8	3.9	100
Padaviya	35.3	14.7	50.0	-	100
Huruluwewa	20.7	-	13.8	65.5	100

Note: 68.1% of the original samples were correctly classified

6.8 Statistical analysis results interpretation related to hydrogeology in NCP

Similarities and dissimilarities related to CKD patient and non-patient samples were further examined using the following relationships of water quality related to hydrogeological characteristics of the area. Both primary and secondary data were in use to interpret the results.

i. Fluoride to alkalinity and pH relations
ii. Fluoride to calcium relation
iii. Fluoride and hardness

6.8.1 Fluoride to alkalinity and pH relations

Alkalinity measurements for the primary data were not available. Therefore, secondary data were analysed for the relation between F^- and alkalinity. With regard to CKD endemic samples from Girandurukotte, Nikawewa and Padaviya, F^- and alkalinity showed a positive correlation whereas non-endemic samples from Huruluwewa showed a negative correlation Figure 6.6. Even though of very small sample sizes, positive correlations were also shown in Medawachchiya (endemic) and Wellawaya (non-endemic) samples.

A positive correlation between F^- and alkalinity has been described in highland groundwater situation by Hem (1959), Bulusu & Pathak (1980) and Edmunds & Smedley (2005). Perera et al. (2008) have shown that high F^- concentration in groundwater occurs mostly in neutral and alkaline water. According to Sri Lankan standard, maximum desirable and permissible levels of alkalinity are 200 and 400 mg/L, respectively. The analysed data showed that both CKD endemic and non-endemic samples have alkalinity levels above maximum desirable level except Girandurukotte.

The F^- and alkalinity relationships can be due to differences in dissolution rates of fluoride bearing minerals as explained by Gaus et al. (2002) and Robertson (1986). This phenomenon has been described due to residence time, where more residence time allows for more dissolution of those minerals (Kim & Jeong 2005, Saxena & Ahmed 2003). Edmunds & Smedley (2005) have explained this positive relationship as higher the well depths, water will have more retention time leading to more F^- leaching.

Fluoride and pH relationship was also examined in secondary data and the results as given in Figure 6.7 showed that F^- values were positively correlated with pH. However Wellawaya and Medawachchiya gave inverse relationships, which could not be concluded due to small sample sizes. According to the results some of the values in the CKD endemic and non-endemic samples had pH levels below 6.5. Perera et al. (2008) also have found 1.5% of shallow wells in Anuradhapura have pH levels below 6.5. High F^- concentrations alkaline to neutral high pH values (7-9) are explained as a result of anion exchange (OH^- for F^-) on some clay minerals and weathered micas as a result of base-exchange (Edmunds & Smedley 2005). Mobilization of F^- at high pH had also been explained by Kim et al. (2012) as desorption of iron oxy-hydroxides in groundwater.

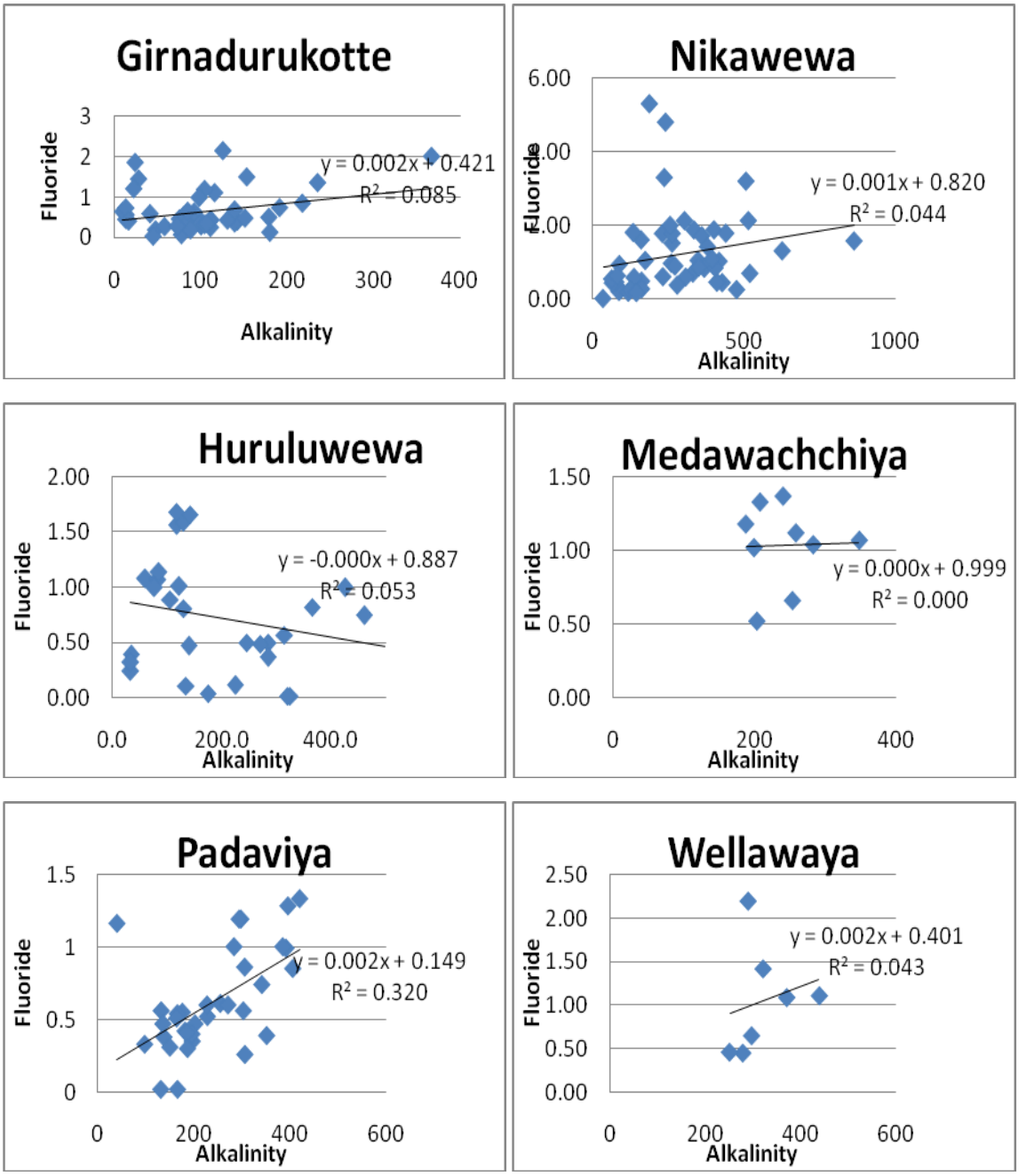


Figure 6.6 Fluoride and alkalinity relations

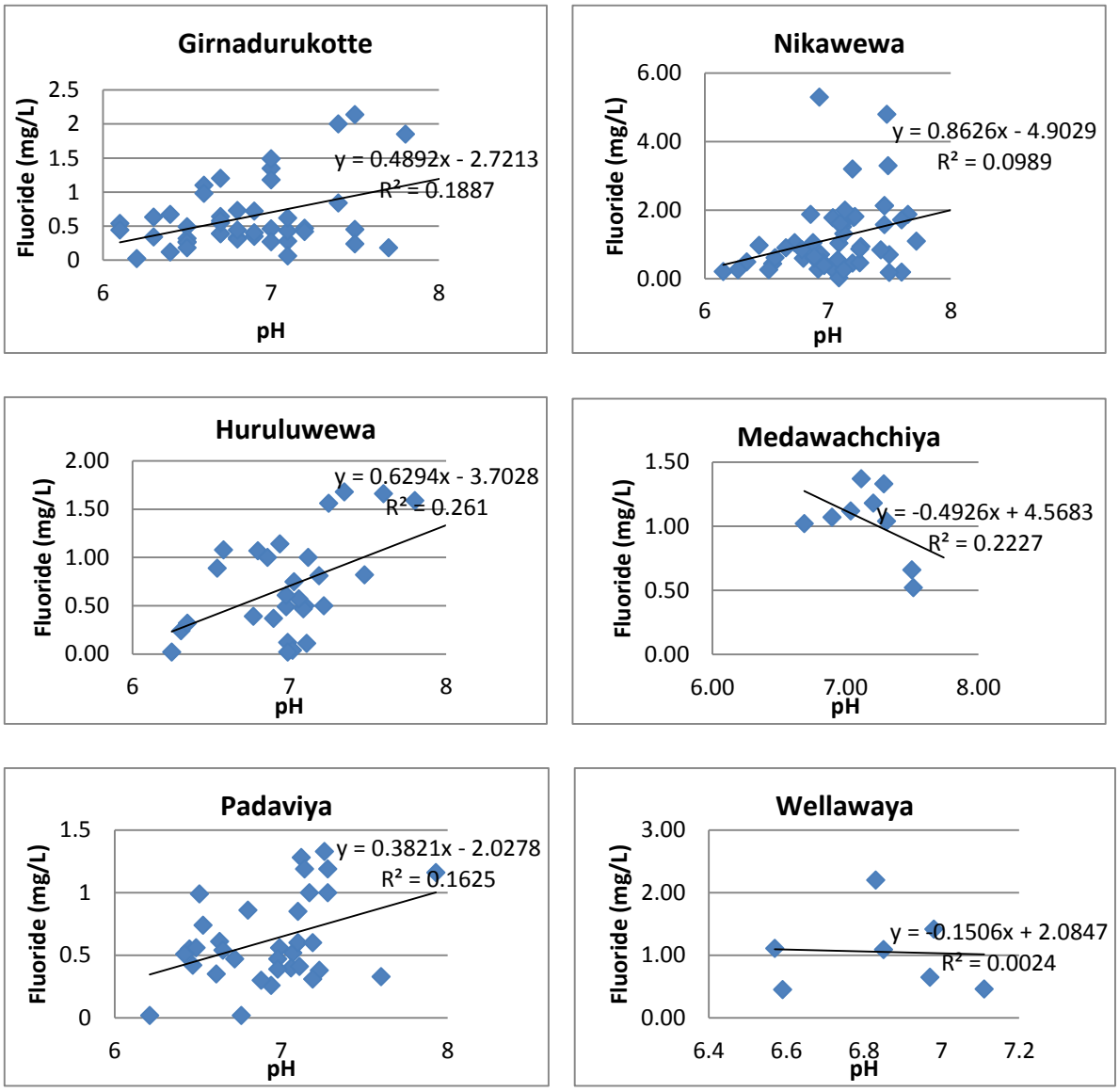


Figure 6.7 Fluoride and pH relations

6.8.2 Fluoride to calcium relation

According to (Ozsvath 2006) dissolved fluoride levels are usually controlled by the solubility of fluorite (CaF_2); where high concentrations are often associated with soft, alkaline, and calcium-deficient waters. This association has also been explained by Edmunds & Smedley (2005) as high dissolved F^- in groundwater depletes Ca^{2+}. This relationship was examined in secondary data and the results are shown in Figure 6.8. In Girandurukotte and Nikawewa CKD endemic samples, F^- to Ca^{2+} were inversely related, however in CKD endemic samples of Padaviya and Medawachchiya, inverse relations were not observed. In CKD non-endemic area samples of Huruluwewa a positive relation was observed.

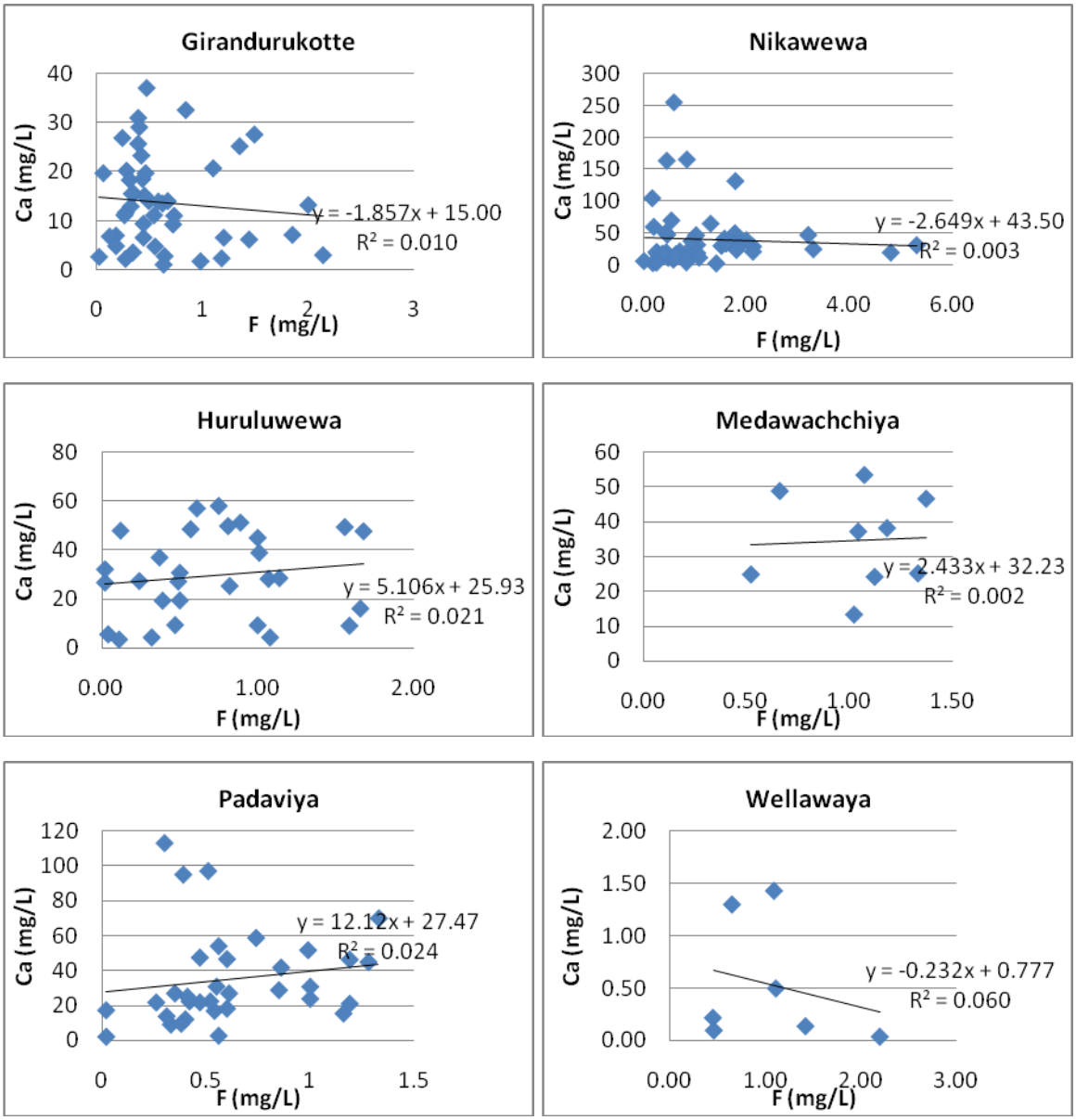


Figure 6.8 Calcium and fluoride relations

6.8.3 Fluoride and hardness

Table 6.16 and also Figure 6.9 show groundwater hardness in different provinces of Sri Lanka. Accordingly it can be noted that Northern, NCP and Central provinces have the levels exceeding the maximum desirable level of 250 mg/L. Perera et al. (2008) has reported high F^- content to be associated with hardness.

Table 6.16 Water hardness, TDS (total dissolved solid) and fluoride levels in groundwater of Sri Lanka

Province	Water hardness, mg/L	Total dissolved ions, mg/L	Fluoride ions, mg/L
Northern	372	1408	0.65
North-western	205	446	0.78
NCP	293	408	1.4
Eastern	250	369	0.76
Central	350	392	0.5
Western	20	80	0.2
Sabaragamuwa	30	58	0.7
Uva	150	360	0.4
Southern	175	392	0.3

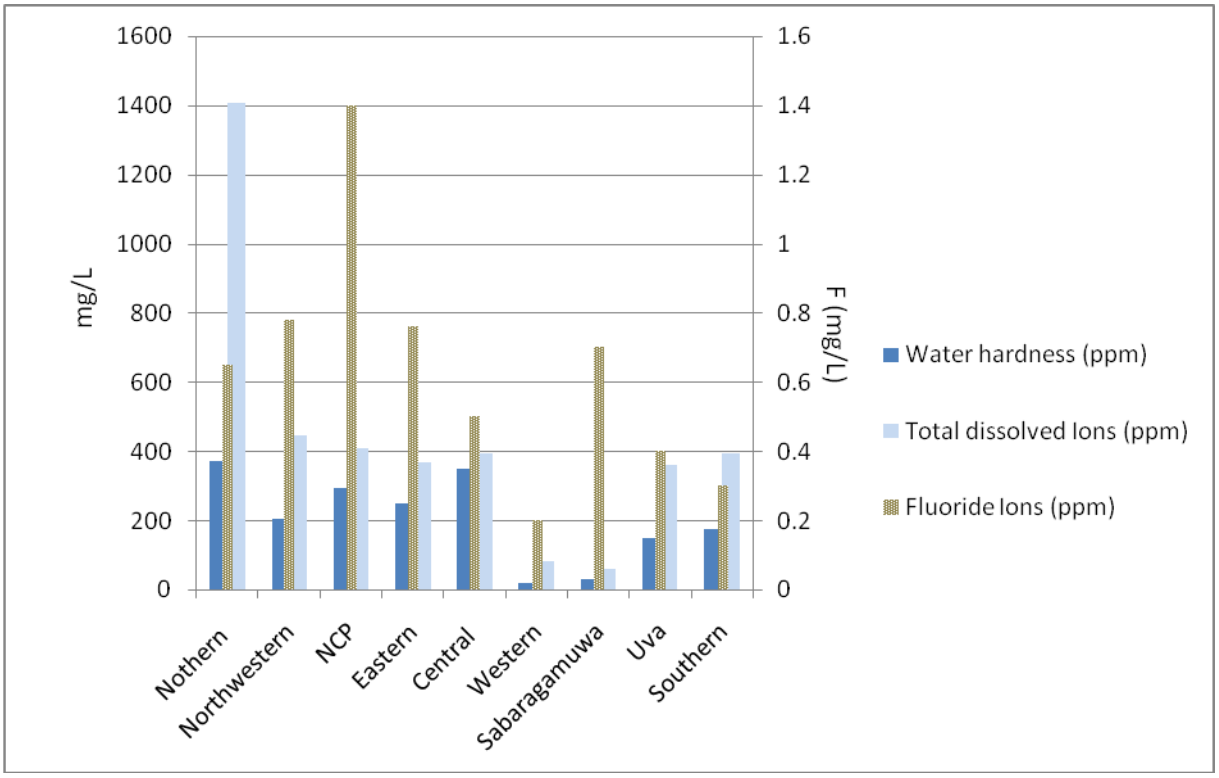


Figure 6.9 Water hardness, TDS (total dissolved solid) and fluoride levels in groundwater of Sri Lanka

Overall it could be concluded that F^- levels in groundwater in CKD endemic areas were positively correlated with pH, Na^+ and alkalinity and negatively correlated with Ca^{2+} and hardness. Enhanced F^- levels in the water samples of NCP may be due to leaching of fluoride-bearing minerals (Herath et al. 2005). In Anuradhapura high F^- incidences have been explained due to minerals like charnockites, charnockitic gneisses, granitic gneisses and

hornblende gneisses (Dissanayake 1991). Other fluoride-bearing minerals include micas, pyroxene, hornblende fluorite, tourmaline, topaz, sphene and apatite (Young et al. 2011). According to Young et al. (2011) high values up to 4.34 mg/L of F^- have been found in the northern part of Anuradhapura where there is granitic gneiss and biotite gneiss are abundant. Biotite is the rock type underlying the CKD affected divisions of Medawachchiya and Nikawewa which were also the sampling areas of this research. According to Dissanayake (1991) biotite gneiss underlying the area has F^- levels of 0.08-3.5% by weight and according to Dharmagunawardhana (2004) biotite and hornblende in granitic gneiss and biotite gneiss in the area may have high F^- contents of 3.5 and 2.9% by weight, respectively. When Gampaha control area was concerned, F^- was not detected in water samples, which were different from CKD endemic samples as the underlying rocks did not have fluoride-bearing minerals.

Panabokke & Ariyaratne (2008) have explained the variability of F^- in groundwater based on hydrogeology where high F^- content are found in interflow sites as well as upwelling sites, whereas low F^- contents have been found in adequate drainage sites. This variation had also been explained as variation of leachability from rocks into water bodies due to maximum solubility not attained due to residence time and differences in dissolution rates of rock materials (Herath et al. 2005). With regard to residence time, shallow groundwater wells are not subjected to longer residence time compared to deep groundwater wells. Rather F^- levels in shallow wells could be more, which may be described by underlying mineralogy and high evaporation influenced by warm conditions that prevail in NCP (Dissanayake 1991). Higher tendency of F^- in entering the aqueous medium and evaporation is bringing the soluble F^- upward.

However according to the primary data it was found that average F^- levels did not exceed WHO standards. As 25% of the samples collected were just after a monsoon period, dilution of wells could be a possible reason for its low levels. At the same time this can be identified as a deficiency of the statistical methods where mean or median values are taken to characterize the samples. This deficiency was overcome by taking pairs of groups for comparison tests as then the conclusions are drawn between sampling groups.

The association of F^- statistics and fluorosis incidents in each of the provinces of Sri Lanka are shown in Figure 6.10. The 1983/84 dental fluorosis numbers and average F^- levels from each of the provinces were obtained from Dissanayake (1991) and Dissanayake et al. (1982), respectively to plot the bars in Figure 6.10. The plotting showed a close pattern in the provinces of Northern, North-western, Southern as well as NCP. These provinces are grouped as lowland dry zone areas according to ecological categorization of Sri Lanka. The community fluorosis index (CFI) has been shown to have a zonal variation with CFI values of 1.81 in Anuradhapura and 1.66 in Polonnaruwa, leading the fluorosis situations in the country (Dissanayake 1991).

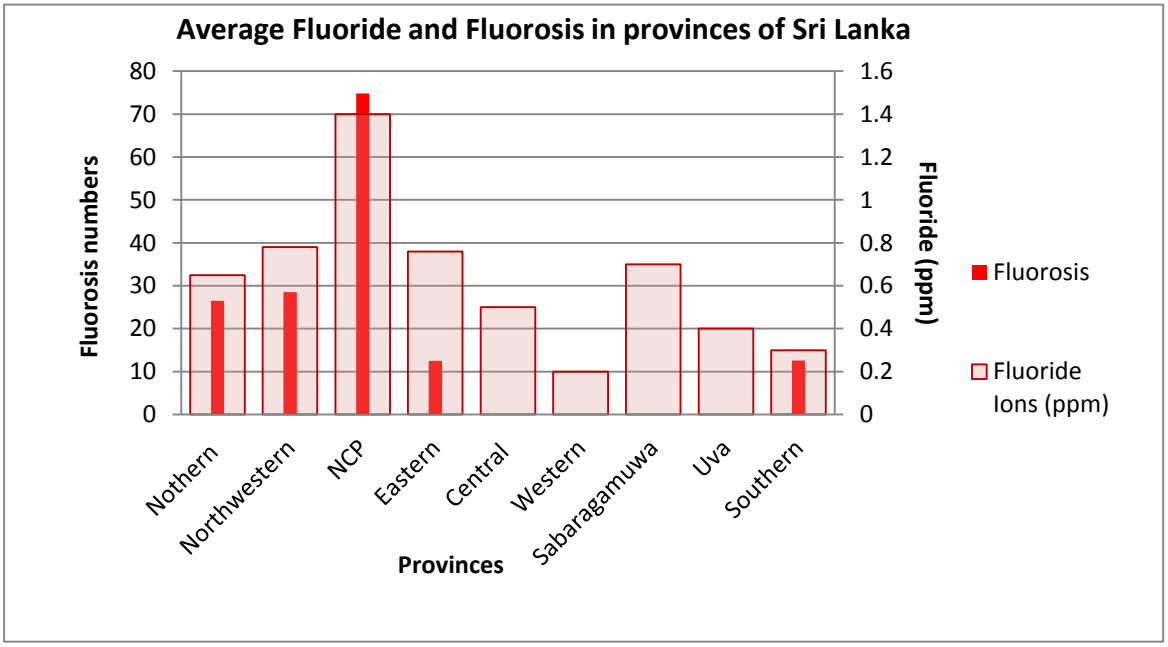


Figure 6.10 Average fluoride levels and fluorosis conditions in provinces of Sri Lanka

6.9 Soil data analysis results in Medawachchiya

From the CKD endemic area of Medawachchiya, a total of 30 soil samples from depths of 30 cm were collected from the vicinity of CKD patient and non-patient water well locations. Another 20 samples were collected from the control area Gampaha. These samples were also analysed for the same variables as in drinking water samples and the results are shown in Table 6.17, Table 6.18 and Table 6.19.

It was noted that in both CKD patient and non-patient soil samples Cl^- were lower compared to control area samples. However F^- levels were slightly lower in the control area than CKD

endemic areas. Nitrates were almost double in the control area than CKD endemic areas while PO_4^{3-} was higher in CKD patient samples only. Calcium, Na^+ and Mg^{2+} were several times higher in both patient and non-patient soil samples compared to control area.

Table 6.17 Soil sample results from the vicinity of CKD patient drinking water sources

	CKD patient soil samples							
		Average	SD	Skewness	Median	CV	Maximum	Minimum
Cl^-	mg/kg	4.50	3.12	0.78	3.50	0.69	11.00	1.00
F^-	mg/kg	16.11	12.83	1.09	9.00	0.80	41.00	4.00
NO_3^-	mg/kg	17.27	9.30	-0.21	19.00	0.54	29.00	4.00
PO_4^{3-}	mg/kg	45.04	59.47	2.91	25.00	1.32	202.40	18.00
Ca^{2+}	mg/kg	1000.08	850.56	0.09	1150.00	0.85	2400.00	0.18
Mg^{2+}	mg/kg	250.67	89.98	0.80	236.50	0.36	417.00	148.00
Na^+	mg/kg	2250.92	1959.82	-0.35	3550.00	0.87	4300.00	32.00

Table 6.18 Soil sample results from the vicinity of CKD non-patient drinking water sources

	CKD non-patient soil samples							
		Average	SD	Skewness	Median	CV	Maximum	Minimum
Cl^-	mg/kg	4.53	3.66	1.10	3.00	0.81	11.00	1.20
F^-	mg/kg	17.91	13.25	0.38	21.00	0.74	39.00	3.00
NO_3^-	mg/kg	20.50	17.77	1.17	15.50	0.87	59.00	3.00
PO_4^{3-}	mg/kg	19.52	14.34	0.14	22.00	0.73	41.00	1.10
Ca^{2+}	mg/kg	923.46	1024.20	1.17	867.00	1.11	3200.00	0.10
Mg^{2+}	mg/kg	294.80	173.29	1.54	252.50	0.59	698.00	136.00
Na^+	mg/kg	2408.24	2038.12	-0.47	3800.00	0.85	4200.00	0.39

Table 6.19 Soil sample results from control area drinking water sources

Soil samples in Control area								
		Average	SD	Skewness	Median	CV	Maximum	Minimum
Cl^-	mg/kg	66.2	70.5	1.39	26	1.06	219	11
F^-	mg/kg	13.5	14.85	0	13.5	1.1	24	3
NO_3^-	mg/kg	39.7	20	-0.12	42	0.5	68	14
PO_4^{3-}	mg/kg	33.44	24.53	1.46	24	0.73	84	10
Ca^{2+}	mg/kg	124.9	313.6	2.82	0	2.51	986	0
Mg^{2+}	mg/kg	86.3	73.43	2.34	63	0.85	278	30
Na^+	mg/kg	123.8	72.76	0.85	89.5	0.59	243	56

It can be noted that in the CKD patient and non-patient soil samples, F- were in the range of 4-41 and 3-39 mg/kg, respectively with averages of 16 and 19 mg/kg. In the control area

samples F- were in the range of 3-24 mg/kg with an average of 14 mg/kg. This clearly showed that F- in CKD endemic soils was higher than in control soil.

6.10 Sodium to calcium ratio

Mean Na/Ca ratios as shown in Table 6.20 were calculated using primary data in the CKD endemic water sampling groups. In Anuradhapura patients the average was 0.68 with a maximum of 2.67, while in Gampaha control area the average was 3.31 with a maximum of 7.26. According to the findings by Chandrajith et al. (2011a), the mean Na/Ca ratios in the CKD endemic areas were in the range of 1.6 to 6.6, while for the non-endemic areas in the range of 4 to 469. As such the Na/Ca ratios of CKD endemic and non-endemic areas of this research were in similar trends to Chandrajith et al. (2011a). In general the endemic ratios were lower than non-endemic ratios as also indicated by Chandrajith et al. (2011a).

Table 6.20 Sodium to calcium ratio of different sampling groups

Sampling group	Average	Median	Maximum	Minimum
ANU-P	0.68	0.52	2.67	0.17
POL-P	0.66	0.48	2.67	0.17
ANU-NP	1.51	1.52	3.74	0.24
POL-NP	0.57	0.48	1.88	0.08
GAM-C	3.31	2.99	7.26	0.25

6.11 Detection of heavy metals

Heavy metals analysed by this research and different other researches in the CKD endemic water samples are shown in Table 6.21. The results showed that the average, median, maximum and minimum values for Fe^{3+}, Cu^{2+}, Zn^{2+}, As^{3-}, Pb^{2+} and Cd^{2+} were below WHO limits. Manganese (Mn^{2+}) in the samples of this research was identified to exceed WHO limit in average and maximum values. It was observed that none of the drinking water samples in Anuradhapura had Cd^{2+} whereas patient and non-patient water samples in Polonnaruwa contained Cd^{2+} but below WHO limit. Cadmium (Cd^{2+}) concentration in water of Gampaha was zero. The studies named in Table 6.21 also found Fe^{3+}, Mn^{2+}, Al^{3+}, As^{3-}, Pb^{2+} and Cd^{2+} were below WHO limits in the CKD endemic areas.

Table 6.21 Heavy metal analytical results in CKD endemic area of Medawachchiya

Heavy metal, mg/L	This research (Anuradhapura and Polonnaruwa samples)				Other research	WHO limit
	Average	Median	Max	Min	Average	
Fe^{3+}	0.237	0.186	0.771	0.0166	Not Detected in Medawachchiya (Chandrajith et al . 2010)	1.0
Cu^{2+}	0.131	0.0071	.0649	0.002	Not Analysed	1.0
Zn^{2+}	0.0617	0.0467	0.158	0.012	Not Analysed	5.0
Mn^{2+}	0.124	0.0215	0.625	0	0.0113 in Medawachchiya (Chandrajith et al. 2010)	0.1
Al^{3+}	Not analysed				Below WHO limits (WHO 2012)	0.2
As^{3-}	<0.02	<0.02	<0.02	<0.02	Below WHO limits (Jayawardena et al. 2012, Wasana et al. 2012, Kawakami et al. 2012, WHO 2012)	0.05
Pb^{2+}	0.0052	0.0047	0.0096	0.0014	Below WHO limits (Jayawardena et al. 2012, WHO 2012)	0.01
Cd^{2+}	<0.01	<0.01	<0.01	<0.01	0.0027-0.007 µg/L (Chandrajith et al. 2010a).	0.05

6.12 Other sources of fluoride in CKD endemic areas

There are many other food stuff as shown in Table 6.22, can add F^- to the diet of ordinary Sri Lankan. For example black tea that is consumed regularly by Sri Lankans as a beverage has been found to have more F^- (a concentration of 60-112 mg/kg) than green tea (Meenakshi & Maheshwari 2006). Rice a staple food, which is locally grown and consumed in NCP, has been found with 5.9 mg/kg F^-. The common vegetables like cucumber and ladies finger, have F^- levels of 4.1 and 4.0 mg/kg, respectively. Mango a main fruit grown in the area for consumption contained 3.7 mg/kg of F^-. Coconut a main ingredient used in cooking contained 5.7 mg/kg of F^- and mustard seed commonly used as a spice contained 5.7 mg/kg F^- (Saxena & Sewak 2015). Also among rural farming families, chewing of beetle leaves, areca nut and dried tobacco are consumed as daily habit. These ingredients are found with F^- levels in the ranges of 7.8-12, 3.8-12, and 3.2-38 mg/kg respectively (Meenakshi & Maheshwari 2006). All these stuff which are consumed on a daily basis by communities in the CKD endemic areas can contribute enhanced F^- in their digestive system.

Table 6.22 Fluoride from different food sources

Food type/source	Fluoride content, mg/kg
Black tea	60-112
Rice	5.9
Cucumber	4.1
Ladies fingers	4.0
Mango	3.7
Coconut	5.7
Mustard seed	5.7
Beetle leaves	7.8-12
Areca nut	3.8-12
Tobacco (dried leaves)	3.2-38

6.13 Summary

Selective chemical parameters of CKD endemic groundwater samples were compared with WHO standards. Patient and non-patient samples were grouped as Anuradhapura patients (ANU-P), Anuradhapura non-patients (ANU-NP), Polonnaruwa patients (POL-P), Polonnaruwa non-patients (POL-NP) and Gampaha control area samples (GAM-C). Descriptive statistics were used to characterise chemical parameters in each sampling group. Simple comparison and complex group comparison tests were applied in those data sets. Statistical analysis methods like Analysis of Variance (ANOVA) with Dunnett's T3 post-hoc test, Kruskal-Wallis (KW) with Mann-Whitney's post-hoc test were used to find whether the selected sampling groups were significantly different. Factorial Analysis (FA) was used to identify the associations of drinking water chemical parameters. Discriminant Analysis (DA) was used to analyse whether sampling groups were appropriately classified.

According to FA results, Anuradhapura patient samples showed significant relations between Na^+ and F^- however non-patient samples did not make a factor combination between Na^+ and F^-. In Polonnaruwa patient samples, Na^+ and F^- combined into a factor but it was equally significant with Mg^{2+} and F^- combined factor. When Polonnaruwa patients and non-patients were compared, patients showed significantly high reliability between Na^+ and F^- combination than non-patients. Ca^{+2} and F^- combination was also more reliable in non-patients. These Mg^{2+} and F^-, and Ca^{+2} and F^- combinations were indicative of less incidences

of CKD in Polonnaruwa compared to Anuradhapura. Discriminant Analysis (DA) showed that most of the sampling groups were correctly classified.

When the secondary data results were compared, the same conclusions could be drawn where Girandurukotte though not in NCP but CKD endemic area, showed similar results as Anuradhapura patient samples. Nikawewa and Padaviya in NCP having CKD patients also showed the same factor results; however Huruluwewa in NCP, a non CKD endemic area showed Mg^{2+} and F^{-} combination was equally significant.

Mean Na/Ca ratios in the CKD endemic areas were within the range identified by Chandrajith et al. (2010b). Heavy metals of Cd^{2+} and As^{3-} were not found in Anuradhapura samples and As^{3-} was not found in Polonnaruwa samples.

Fluoride richness in groundwater of CKD endemic areas can be due to leaching of fluoride-bearing minerals and enhanced alkalinity of the soils. Higher tendency of F^{-} is entering the aqueous medium and evaporation is bringing the soluble F^{-} upward due to high temperature. Additionally there are many other foods consumed that can add F^{-} to the diet of the people in the CKD endemic area. As such F^{-} pollution could be the probable CKD causing factor in the endemic areas of Sri Lanka.

7 RESULTS AND DISCUSSIONS - CKD MITIGATION TECHNIQUES

Rainwater harvesting (RWH) has been discussed in this chapter as a CKD mitigation technique. Rainwater harvesting (RWH) tank estimations were carried out by Mass curve method using daily and monthly rainfall data. Eight rainfall stations located within close proximity to CKD endemic households in Anuradhapura and Polonnaruwa were used for this analysis. Those tank estimations were further analysed for volumetric reliability, which gave an account of how much reliability changed if tank size was changed. Also tank estimation results were subjected to sensitivity analysis with respect to catchment runoff coefficient, per capita consumptions and number of persons in a family.

7.1 Rainfall statistics

Monthly rainfall stations considered for this analysis were: AN487, AN109B, AN487A and AN410A from Anuradhapura and PL93B, PL134A, PL141A and PL162 from Polonnaruwa. Year-wise total rainfall data for Anuradhapura (2001-2011) and Polonnaruwa (2001-2010) rainfall stations are shown in Figure 7.1 and Figure 7.2. Those stations are situated closest to the CKD patient areas in each district. Monthly rainfall values were obtained from daily rainfall data. Average annual rainfalls of each station for the periods in question are given in Table 7.1. It also includes the total rainfall for a year when the minimum rainfall occurs in that station.

7.2 Runoff surface area estimation

To calculate runoff surface area (*A*) required for each rainfall station, Equation (4.3) (given in Methodology chapter) was used. Runoff surface area estimations were carried out using both monthly and daily rainfall data. For runoff surface area estimation, monthly based least hydrological year rainfall value was in use. Similarly daily based least hydrological year rainfall value was in use. Runoff surface area (*A*) estimations using daily based least hydrological year rainfall data (932.7 mm from 10th October 2009 to 9th October 2010), for rainfall station AN109B is shown below.

$$A = \frac{4 \times 6 \times 365}{0.75 \times 932.7}$$

7.3 Tank size estimations

Mass curve method to estimate tank sizes using monthly rainfall data for station AN410A is given in Table 7.2 and Figure 7.3. For this station, the hydrological year with least rainfall was October 2008 to September 2009 (first column of the table). The second column shows the rainfall amount in those months. Rainwater harvesting potential (RWHP) was estimated using Equation (4.2). Rainwater demand of a family was estimated using Equation (4.1). Runoff surface area for station AN410A using monthly rainfall was 10.5 m^2 and the runoff coefficient (R_C) value of 0.75.

Tank size estimations based on monthly and daily rainfall data are given in Table 7.3 and Table 7.4 respectively, which were between 2900 and 5200 L. Tank size estimations based on daily rainfall data were bigger than those based on monthly rainfall data for all the stations. This is due to daily variations in rainfall frequency and quantity. In monthly based calculations the number of days in a month was assumed to be 30 and in yearly based calculations the number of days in a year was considered as 365. In all the calculations the average drinking water requirement per person was considered as 6 L/day and the average family size as 4 members. Therefore the average family requirement was considered to be 720 L/month or 8760 L/year using daily demand. Overall tank estimations showed that tank sizes were bigger for lower average annual rainfall stations than those stations with bigger average annual rainfall values. Minimum runoff surface area estimations based on daily and monthly rainfall data were between 6.7 and 18.2 m^2.

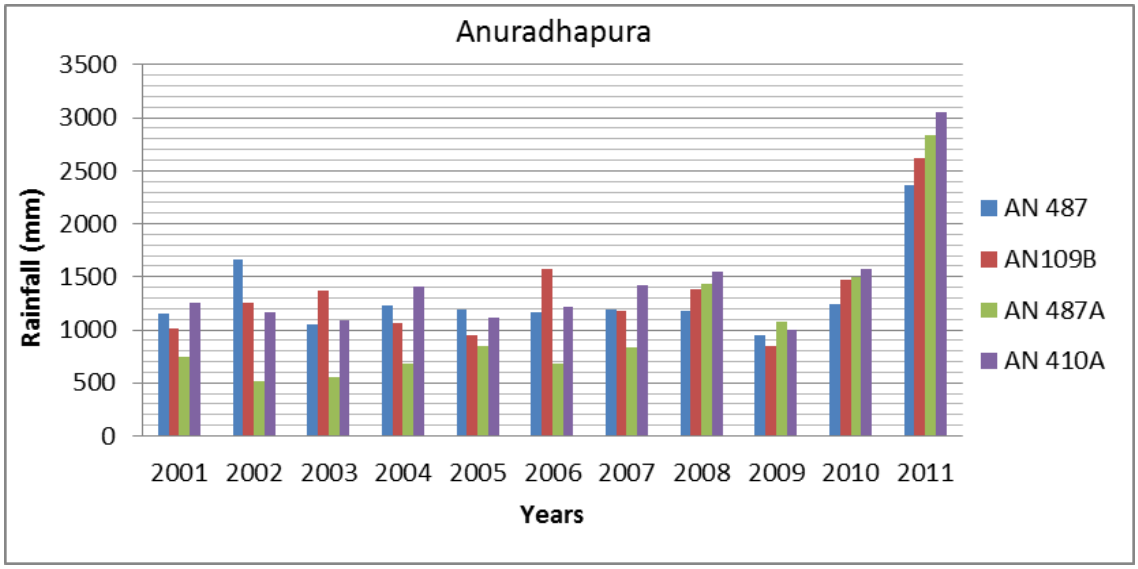


Figure 7.1 Yearly wise rainfall (2001-11) of 4 stations situated closest to the CKD patient areas in Anuradhapura district

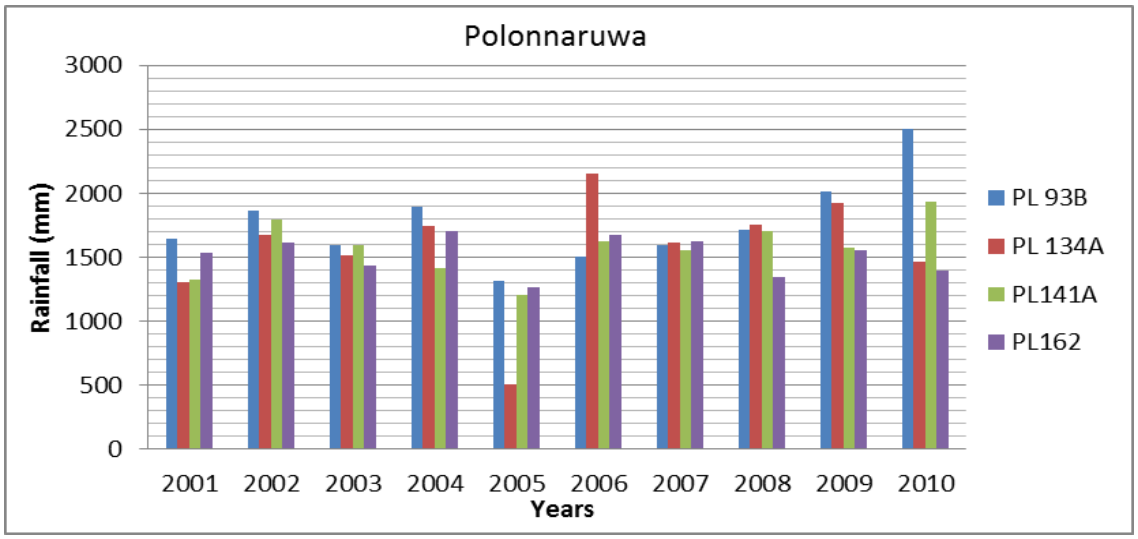


Figure 7.2 Yearly rainfall (2001-10) of 4 stations situated closest to the CKD patient areas in Polonnaruwa district

Table 7.1 The average annual rainfall and minimum rainfall values in 2001-11

Location	Rainfall station	Average annual rainfall (mm/year)	Minimum annual rainfall (mm/year)
Anuradhapura	AN 487	1307.5	994.7
	AN 109B	1383.6	842.5
	AN 487A	1196.8	521.9
	AN 410A	1489.8	997.5
Polonnaruwa	PL 93B	1767.5	1311.2
	PL 134A	1565.5	503
	PL 141A	1572.8	1203.3
	PL 162	1516.9	1268.2

For the same rainfall station (AN 109B), monthly based least hydrological year rainfall value was found as 931.7 mm which was from 1st October 2009-to 30th September 2010. So both the values were very similar which gave a runoff surface area of approximately 12.5 m^2. Depending on monsoonal rainfall commencing day, *R* values in some rainfall stations were higher for daily based least hydrological year than monthly based least hydrological year. However in some instances both *R* values were equal. When the *R* values were higher it gave smaller runoff surface area estimations. As a result daily based rainfall estimations gave smaller runoff surface area values than monthly based rainfall estimations for certain stations. Minimum runoff surface area estimations based on monthly and daily rainfall data are given in Table 7.3 and Table 7.4 respectively.

Table 7.2 Rainwater tank calculation using monthly rainfall data for station AN 410A

Month	R, mm	RWH, L/month	Cumulative demand (D), L	Cumulative supply/ storage, L	Cumulative surplus, L	Required tank Volume = max - min storage, L
October	208.1	1638.79	720	1638.79	918.79	
November	214.9	1692.34	1440	3331.13	1891.13	
December	242.4	1908.90	2160	5240.03	3080.03	2973.26
January	41.3	325.24	2880	5565.26	2685.26	
February	0	0.00	3600	5565.26	1965.26	
March	179.5	1413.56	4320	6978.83	2658.83	
April	73.6	579.60	5040	7558.43	2518.43	
May	34.9	274.84	5760	7833.26	2073.26	
June	16.5	129.94	6480	7963.20	1483.20	
July	0	0.00	7200	7963.20	763.20	
August	95.5	752.06	7920	8715.26	795.26	
September	4	31.50	8640	8746.76	106.76	
Totals	1110.7	56160.00				

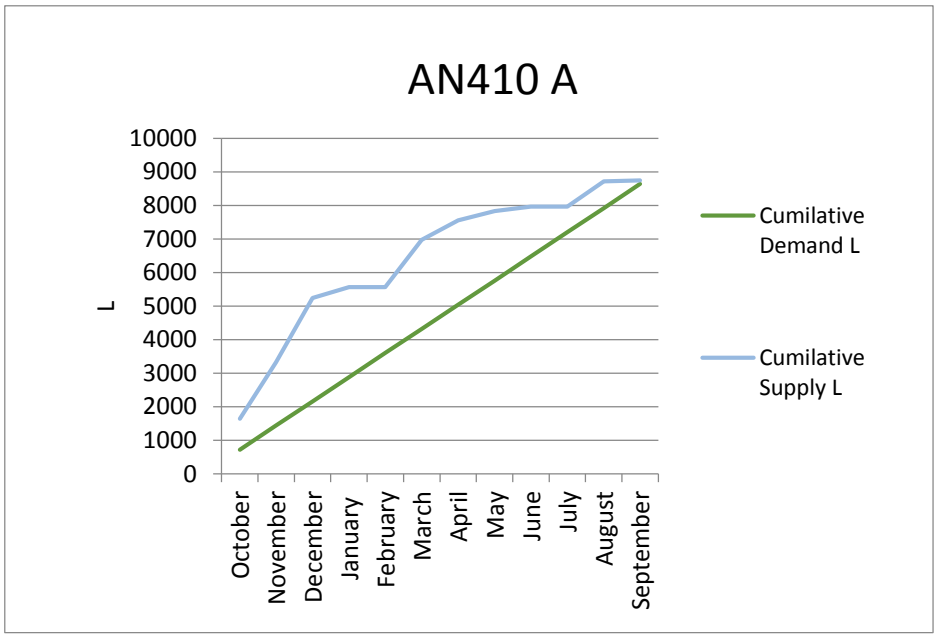


Figure 7.3 Rainwater tank calculation using monthly rainfall data for station AN410A

Table 7.3 Minimum runoff surface area and tank size estimations using monthly rainfall data.

Station name/ID		Minimum rainfall hydrologic year	Rainfall, mm/year	Runoff surface area, m^2	Tank size, L
Anuradhapura	AN 487	Oct 2008-Sept 2009	973.3	12.0	3363.9
	AN 109B	Oct 2009-Sept 2010	931.7	12.5	4157.8
	AN 487A	Sept 2004-Aug 2005	641.3	18.2	5136.4
	AN 410A	Oct 2008-Sept 2009	1110.7	10.5	2973.2
Polonnaruwa	PL 93B	Oct 2005-Sept 2006	1269.5	9.2	3871.4
	PL 134A	Oct 2004-Sept 2005	1619.2	7.2	4201.9
	PL 141A	Sept 2004- Aug 2005	1344.9	8.7	2922.9
	PL 162	Oct 2004- Sept 2005	1752.6	6.7	3238.0

Table 7.4 Minimum runoff surface area and tank size estimations using daily rainfall data

Station name/ID		Minimum rainfall hydrologic year	Rainfall, mm/year	Runoff surface area, m^2	Tank size , L
Anuradhapura	AN 487	11 Oct 2008-10 Oct 2009	973.3	12.0	3882.9
	AN 109B	10 Oct 2009-09 Oct 2010	932.7	12.5	4481.8
	AN 487A	26 Aug 2004-25 Aug 2005	667.8	17.5	5161.1
	AN 410A	4 Oct 2008-03 Oct 2009	1110.7	10.5	3450.9
Polonnaruwa	PL 93B	2 Oct 2005-01 Oct 2006	1269.5	9.2	4130.0
	PL 134A	12 Oct 2004-11 Oct 2005	1619.2	7.2	4909.3
	PL 141A	24 Sept 2004-23 Sept 2005	1337.6	8.7	3715.7
	PL 162	1 Oct 2004-30 Sept 2005	1752.6	6.7	3500.7

7.4 Dimensionless graphs

Tank storage and water demand were plotted as a percentages of average annual rainfall to create dimensionless graphs. The dimensionless graphs estimated for rainfall stations in Anuradhapura and Polonnaruwa using daily and monthly rainfall data are shown in Figure 7.4 and Figure 7.5 respectively. Dimensionless graphs can be used to determine the tank size for any household demand. For example in station AN487 based on daily rainfall, a given family demands 60% of average annual supply (by rain), the tank size would be 19.5% of average annual supply. As the average annual supply by rainfall was known for the station, the required tank size would be average annual supply multiplied by 19.5%. Average annual supply for a given household is a function of rainfall amount, runoff surface area and R_c.

Dimensionless graphs showed that tank storage sizes in most of the cases were not linearly varying with household demands. As an example for station AN487 the dimensionless graph using daily rainfall data showed if average annual demand increased from 50 to 100%, the storage as a percentage of the average annual supply did not double, rather it tripled to 45%. It was due to the fact that tank size was not just a function of demand but also a function of rainfall pattern. Thus tank size estimation for one rainfall station cannot be used to estimation tank sizes for other stations as the intercept (c) and slope (m) of each dimensionless graph varied with volume and frequency of rainfall occurrences.

Differences in rainwater tank sizes based on monthly and daily rainfall data were compared using t-test to show the significant differences in slopes of all dimensionless graphs. Table 7.5 shows t-test results for equality of slopes with $p > 0.05$ (at 95% confidence interval) to indicate alternative hypothesis is true, which means the slopes of daily and monthly based dimensionless graphs are not significantly different. However there were considerable differences estimated using dimensionless graphs based on daily and monthly rainfall values. It was due to graph intercepts where the minimum tank sizes based on daily rainfall values were consistently bigger than those based on monthly data. This indicated that even with equality of slopes in dimensionless graphs in daily and monthly based data, there were obvious volume differences in storage tank design. Tank estimates gave bigger sizes for daily rainfall data than monthly data due to refined rainfall quantity distribution in daily

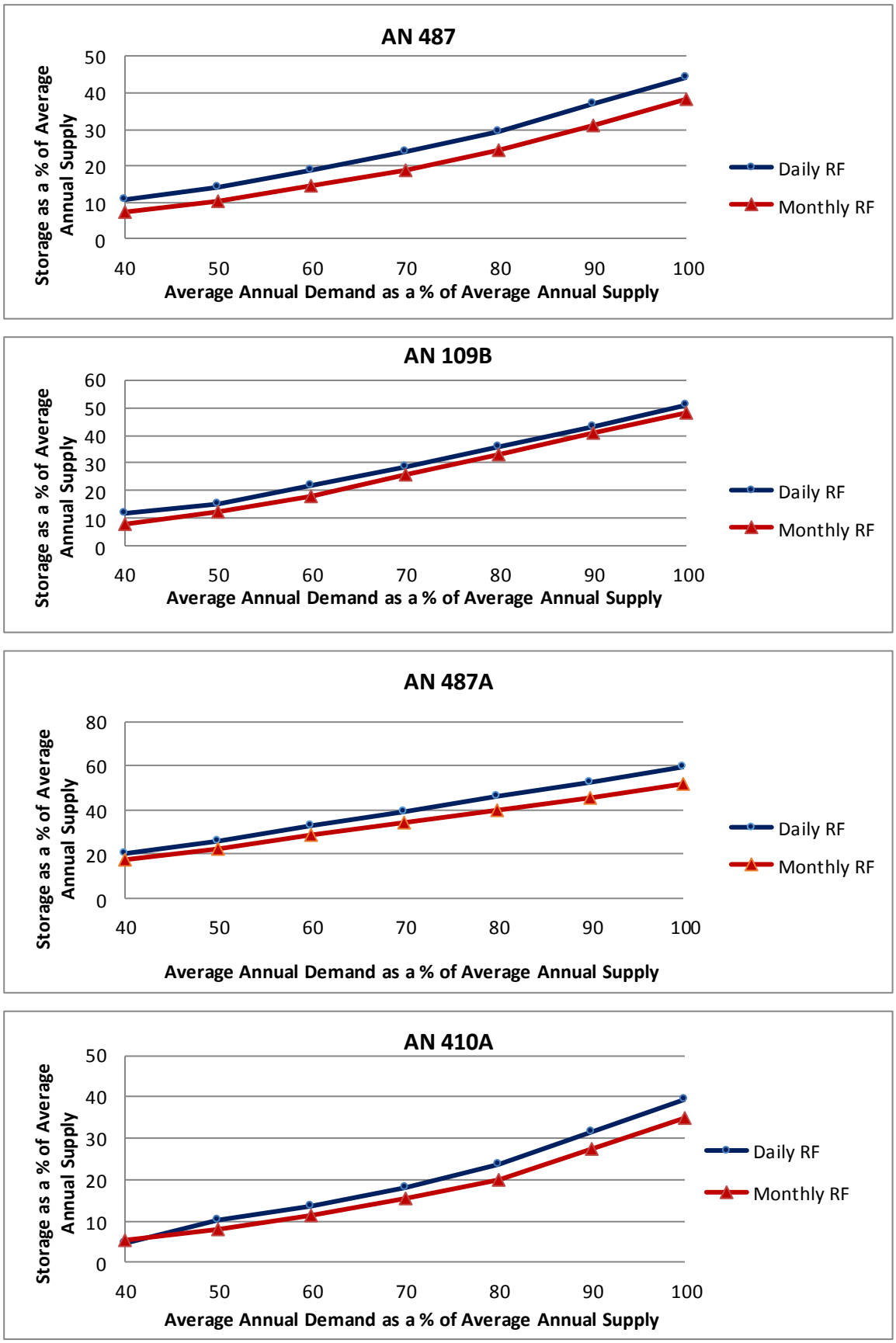


Figure 7.4 Dimensionless Graphs based on daily and monthly rainfall data in Anuradhapura

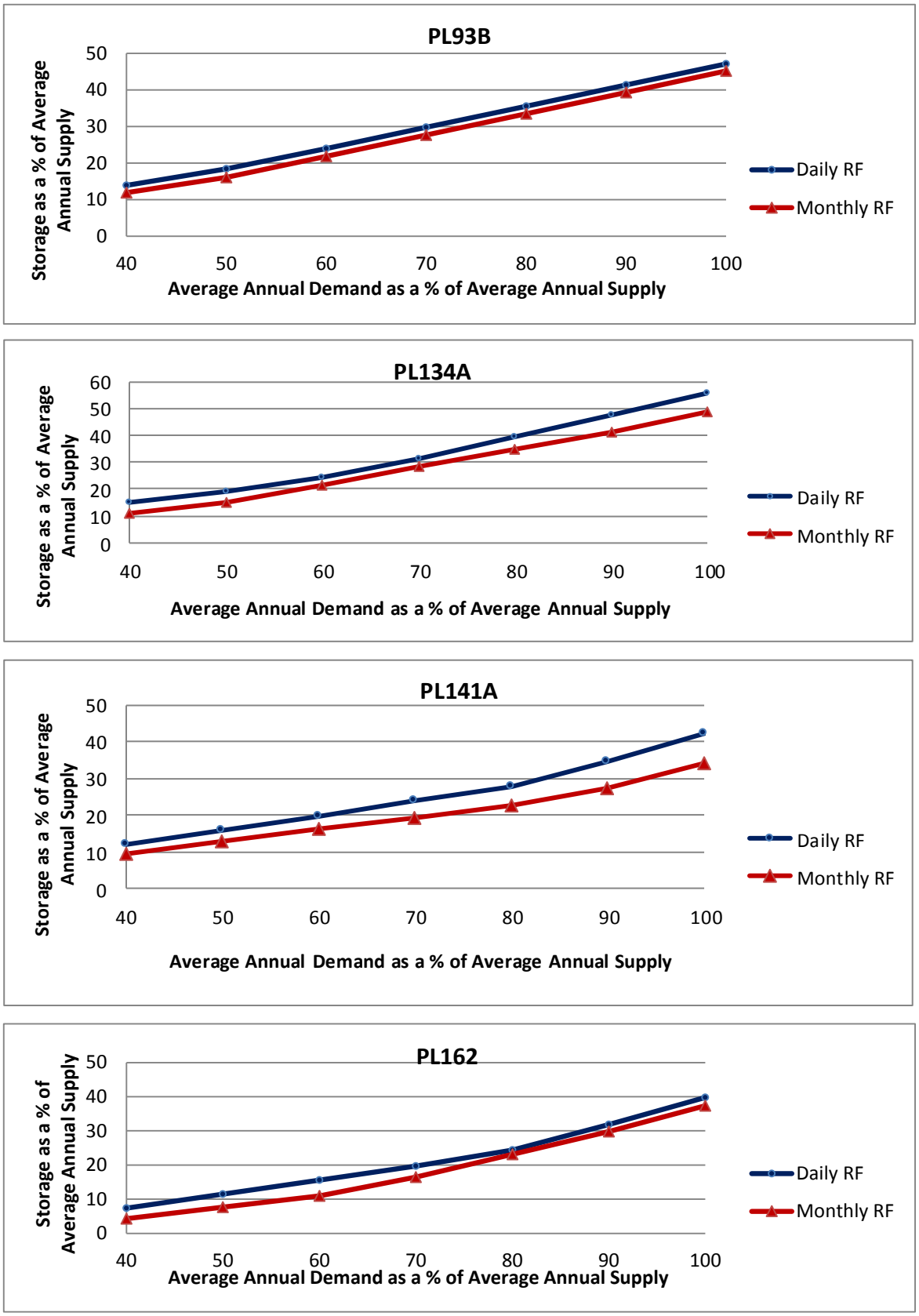


Figure 7.5 Dimensionless Graphs based on daily and monthly rainfall data in Polonnaruwa

calculations. As such daily based rainfall data gave better estimation in calculating required tank sizes than monthly based rainfall data.

Table 7.5 t-test results for equality of Dimensionless graph slopes

Station ID number	AN 487	AN 109B	AN 487A	AN 410A	PL 93B	PL 134A	PL 141A	PL 162
p value	0.46	0.69	0.48	0.66	0.75	0.56	0.36	0.65

7.5 Volumetric reliability analysis

After the tank sizes were estimated, tank sizes were analysed for volumetric reliability. Three levels of volumetric reliabilities 60, 80 and 100% demand levels as percentages of average annual supply were considered in this analysis. The volumetric reliability results for Anuradhapura and Polonnaruwa rainfall stations are given in Annexures 8 and 9. These results showed that bigger tank sizes were required to supply water for increasingly higher demands at a given reliability level. As the tank estimates for different stations were different, the volumetric reliability for each demand was also different. Volumetric reliability plots showed how much reliability changed when tank sizes changed. As an example for station AN487, optimum tank for supply of 100% demand was 3882 L (with a catchment surface of 12 m^2) based on daily rainfall. If a 2500 L tank was constructed, the tank would supply water to satisfy less than 80% of their demand. As such depending on the family water requirement (demand), reliability graphs can be used to determine the size of the tank that would be required for a family to supply water at a given reliability level.

7.6 Sensitivity of the developed Mass curve model

Sensitivity analysis results for Anuradhapura and Polonnaruwa stations were estimated for varying R_c values (Annexures 10 and 11), per capita consumptions (Annexures 12 and 13) and household numbers (Annexures 14 and 15). Annexures 10 and 11 showed that required tank sizes decreased with increasing R_c values. It also showed that if the R_c value is higher, a smaller runoff surface can serve a given tank size. On the other hand a smaller tank size can be compensated with a bigger runoff surface. Therefore, a household with a smaller tank can be filled with a bigger runoff surface or with a catchment surface with a higher R_c value (Annexures 10 and 11 showing a 5 persons household and Annexures 16 and 17 showing a 6

persons household). However sensitivity results showed that plotting became insensitive after certain R_c and runoff surface values. For example for station PL162 when the runoff surface area was more than 16 m^2, tank size became insensitive to R_c and runoff surface area due to the reason that the requirement of 6 L/day for 5 persons (Annexures 10 and 11) or 6 persons (Annexures 16 and 17) was more than fulfilled with a roof area of 16 m^2. Therefore tanks size can be compensated with the runoff surface area only up to a certain value.

Tank size increased with higher per capita consumptions (Annexures 12 and 13) and increasing number of persons (Annexures 14 and 15) in a family due to more water requirement. The given graphical illustrations allow a household with a given per capita consumption and family size to determine the required tank size depending on the runoff surface type and area.

7.7 Summary

Eight rainfall stations located within close proximity to CKD endemic households in Anuradhapura and Polonnaruwa were used to estimate rainwater harvesting tank sizes in this analysis. As a first step runoff surface area (*A*) required for each rainfall station were calculated. In some rainfall stations, rainfall (*R*) values were higher for daily based least hydrological years than monthly based least hydrological years. Those stations gave smaller runoff surface areas as those estimations were inversely related to rainfall.

Tank sizes estimated using mass curve method were between 2900 and 5200 L. Tank estimations were bigger when based on daily rainfall data than monthly rainfall data. It was due to daily variations in rainfall frequency and quantity. Also bigger tank sizes were obtained for stations having lower average annual rainfall values than for those with bigger average annual rainfall. Results indicated that bigger tanks are required to fulfil demands when there is a limited supply of rainfall, either less frequent or smaller supply.

Dimensionless graphs were designed to determine tank sizes depending on household demands. Due to varying volume and frequency of rainfall occurrences in given stations, dimensionless graphs showed different intercepts (*c*) and slopes (*m*). As such it was concluded that a dimensionless graph constructed for one station cannot be used to estimate tank sizes for another station. Due to varying volume and frequency of rainfall

occurrences in given stations, tank sizes estimated using daily rainfall gave bigger tank sizes than those based on monthly data which was indicated by different intercepts (c) in dimensionless graphs.

Volumetric reliability results showed that higher reliability can be obtained with bigger tank sizes for a given demand. Sensitivity analysis results showed that, a smaller tank sizes can be compensated with bigger runoff surfaces or smaller runoff surfaces having higher R_c values. However tank sizes became insensitive to R_c and runoff surface area values after a certain level when the tank sizes are more than fulfilled with a given runoff surface or a surface having a bigger R_c value adequate to fill a tank. Tank size increased with higher per capita consumptions, and the number of persons in a family as more demand needs to be fulfilled by a tank.

8 RESULTS AND DISCUSSIONS - USE OF NATURAL ADSORBENTS FOR FLUORIDE REMOVAL IN WATER

Lab experimental results on the use of natural adsorbents for fluoride removal are given in this chapter. Equilibrium and kinetic model parameters and effect of other physical parameters on batch adsorption were analysed. Column experimental results and adsorbent regeneration are also discussed. Removals of fluoride according to environmental regulations of Sri Lanka are presented in this chapter. Finally a CKD minimization plan was prepared for the CKD endemic areas in question.

8.1 Selection of natural adsorbents

Grounded turmeric (*Curcuma longa*) and ginger (*Zingiber officinale*) rhizome and curry leaves (*Murraya koenigii*) were tested for fluoride adsorption capacity. These ingredients are readily available in households for domestic use by farming families in NCP. Turmeric powder gives an aroma when used in cooking and is traditionally used as local water purifier in Sri Lanka and India. Also turmeric is considered as an antiseptic which is mixed with water and sprayed in households. On the other hand grounded ginger is added only in cooking for its flavour but not in drinking water. Ginger is also believed to have many medicinal values in traditional medicine in Sri Lanka. It is popularly known to heal stomach-ache related to poor digestion. Curry leaves are commonly added to curries which add flavour and aroma to the food. They are also commonly grown in the household gardens in Sri Lanka and available at no cost.

In the analysis turmeric powder showed highest adsorption capacity than ginger and curry leaves as shown in Figure 8.1 and therefore turmeric was chosen for further study. When these adsorption materials were compared for practicality, curry leaves had a problem as these tend to float on water, while ginger taste in drinking water was not pleasant.

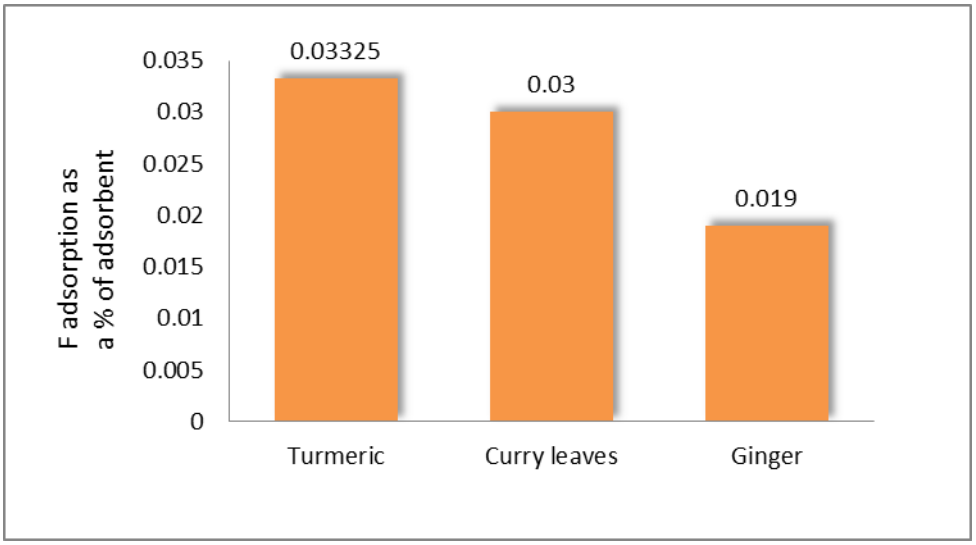


Figure 8.1 Results of column experiments on fluoride adsorption as a % of adsorbent for different adsorbents

8.2 Batch experimental results

8.2.1 Fitting of adsorption isotherm models

Adsorption capacity of turmeric powder was investigated using batch experiments. The amount of fluoride adsorbed per unit mass of adsorbent at equilibrium (mg/g) were obtained using Equation (5.1) (given in the Methodology chapter). Fluoride solution concentration was varied each time (between 1.2 and 20.5 mg/L) but other variables were kept constant including the amount of turmeric powder added (e.g. 0.01 g of turmeric powder to 500 mL of fluoride solution), the room temperature (24±2°C) and the magnetic stirring speed (340 rpm).

According to the results it was observed that the adsorption capacity (qe) increased with increased initial concentration of fluoride solution (adsorbate) when the other variables were kept constant (Table 8.1and Figure 8.2). According to literature it was found that maximum fluoride concentration in CKD endemic areas of NCP was around 9 mg/L. Therefore, fluoride concentrations of 1-20 mg/L were used for further investigation.

Table 8.1 Adsorption capacity as a function of initial weight of absorbent

W, g	C_i, mg/L	C_e, mg/L	(C_i-C_e), mg/L	V, litre	q_e, mg/g
0.01	1.21	0.94	0.27	0.5	13.5
0.01	2.30	1.91	0.39	0.5	19.5
0.01	4.16	3.78	0.38	0.5	19.0
0.01	4.55	3.98	0.57	0.5	28.5
0.01	10.1	9.17	0.93	0.5	46.5
0.01	20.5	18.1	2.40	0.5	120

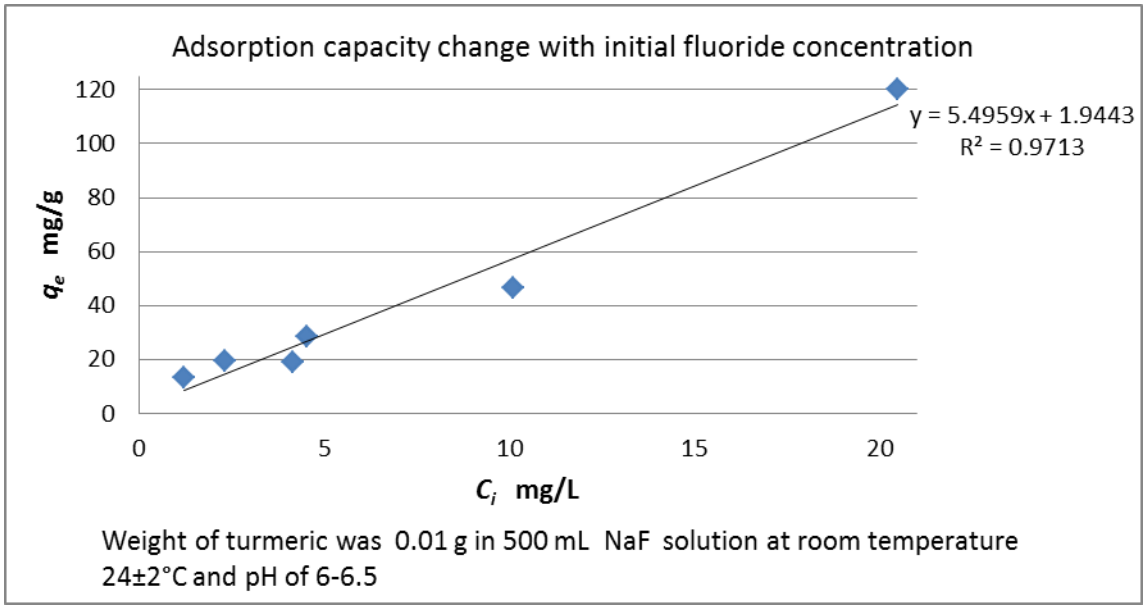


Figure 8.2 Adsorption capacity as a function of initial concentration of fluoride

Batch adsorption tests showed fluoride adsorption capacity on turmeric reached an equilibrium after a period of time. The equilibrium of adsorption process was interpreted by Freundlich and Langmuir isotherms. The calculated Langmuir and Freundlich isotherm model parameters are shown in Table 8.2

The experimental results were applied to the linear form of the Langmuir isotherm as in Equation (5.5). The Langmuir model isotherm was plotted with $1/C_e$ versus $1/q_e$ (Figure 8.3), where C_e is the fluoride concentration at equilibrium (mg/L) and q_e is the amount of fluoride adsorbed per unit mass of adsorbent at equilibrium (mg/g). This plot gave a straight line (R^2 = 0.933) indicating the applicability of Langmuir isotherm to the batch test results with monolayer adsorption to turmeric powder.

Table 8.2 The Langmuir and Freundlich isotherm model parameters

Langmuir isotherm model parameters		Freundlich isotherm model parameters	
b (L/mg)	0.055	n	0.92
Q_o (mg/g)	192.30	k_f (mg/g)	0.118
R^2	0.93	R^2	0.90

(0.01 g turmeric was used in 500 mL fluoride solution at room temperature of 24±2°C and pH 6-6.5)

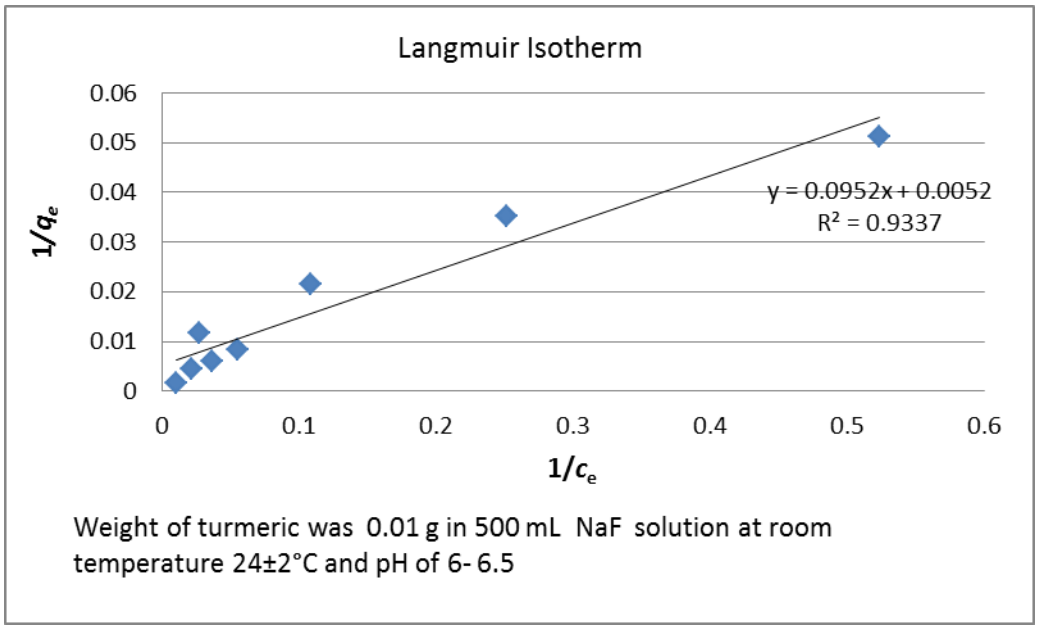


Figure 8.3 Experimental results applied to Langmuir isotherm model

Secondly experimental results were applied to Freundlich isotherm model equation given by Equation (5.7). It was a plot of *log* q_e vs *log* C_e, where C_e is the fluoride concentration at equilibrium (mg/L) and q_e is the amount of fluoride adsorbed per unit mass of adsorbent at equilibrium (mg/g). When the experimental results were fitted to log form of Freundlich isotherm model in Figure 8.4, regression line gave a lesser fit (R^2 = 0.90) than Langmuir isotherm model.

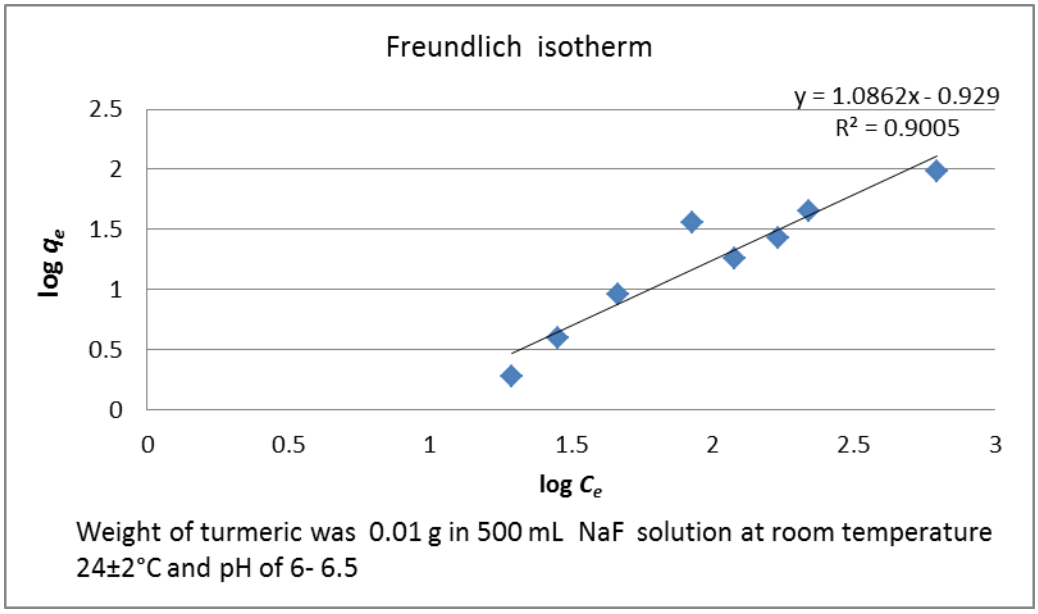


Figure 8.4 Experimental results applied to Freundlich isotherm model

With the linearized equation of Freundlich isotherm model, temperature dependent constants of k_f and $1/n$ were calculated where k_f was Freundlich constant related to adsorption intensity, indicative of surface heterogeneity of the sorbent; and n was an empirical parameter which was a function of the strength of adsorption in the adsorption process. If $1/n > 1$, bond energies decreased with surface density and when $1/n = 1$ all surface sites were equivalent. According to the calculation, $1/n$ was 1.09 to indicate the bond energies decreased with surface density of adsorbent.

However as experimental data fitted both Langmuir and Freundlich isotherm models with $R^2 > 0.9$, it could be concluded that both were more-or-less valid. However, Langmuir isotherm could be identified as a better model to describe fluoride adsorption on turmeric as monolayer coverage.

8.2.2 Fitting of adsorption kinetic models

Fluoride adsorption with time was studied with initial fluoride concentrations of 1, 2 and 5 mg/L while other variables were kept constant (weight of turmeric 0.01 g in 25 mL NaF solution; room temperature 24±2°C and pH of solution 6-6.5). A plot of q_t vs t (min) was plotted where q_t (mg/g) is the amount of fluoride adsorbed per unit mass of adsorbent at any time t. The plots in Figure 8.5 showed that adsorption increased with time and the rate

of adsorption was initially higher which slowed down after about 35 minutes reaching equilibrium after approximately 70 minutes.

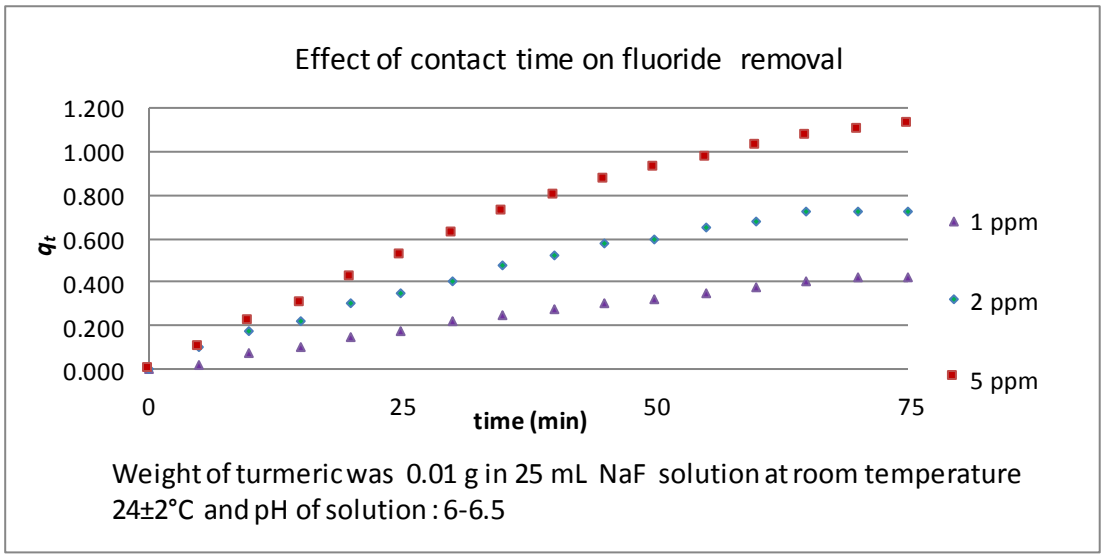


Figure 8.5 Fluoride adsorption by turmeric powder with time

The experimental results on fluoride adsorption with contact time *t* (for fluoride concentrations of 1, 2 and 5 mg/L) were applied to Lagergren first order kinetic model (also known as pseudo first-order kinetic model as shown in Equation (5.8)) and pseudo second-order kinetic model (as shown in Equation (5.10)) are shown in Figure 8.6 and Figure 8.7 respectively.

The experimental data fitted well to the linearized form of pseudo first-order kinetic model ($R^2 > 0.99$). It indicated that the experimental results obey the Lagergren first order kinetic model assumptions. The pseudo first-order rate constant k_l and q_e (the amount of fluoride adsorbed per unit mass of adsorbent in mg/g at equilibrium) values were determined for each adsorbent concentration from the slope and the intercept of the corresponding plots as listed in Table 8.3.

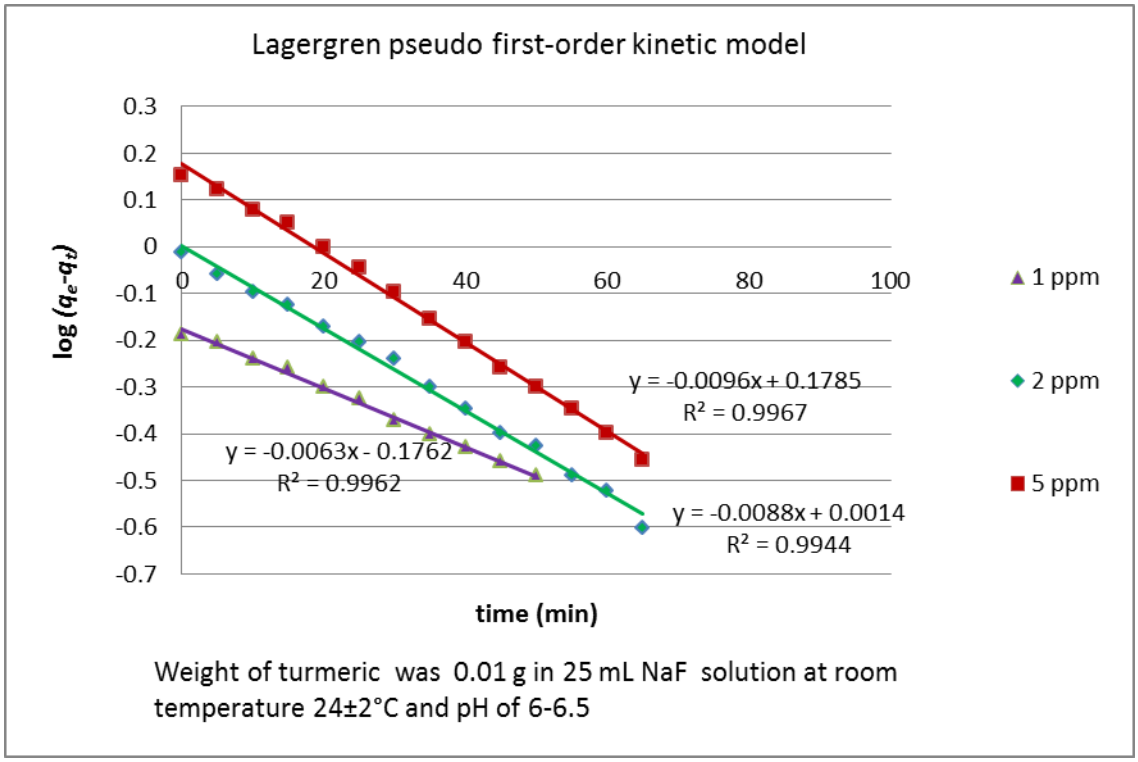


Figure 8.6 Adsorption results applied to Lagergren first-order kinetic model

Table 8.3 Lagergren first-order kinetic model parameters for different fluoride concentrations

Fluoride concentration, mg/L	R^2	k_1 (min^{-1})	q_e (cal) mg/g	q_e (expt) mg/g
1	0.9962	0.014	0.666	0.675
2	0.9944	0.020	1.003	0.975
5	0.9967	0.022	1.508	1.425

(weight of turmeric was 0.01 g in 25 mL fluoride solution at room temperature 24±2°C and pH of 6-6.5)

Pseudo second-order kinetic model parameters were calculated for different initial fluoride concentrations of 1, 2, and 5 mg/L The experimental data were fitted into the linearized form of pseudo second-order kinetic model with t/q_t vs t (min) where q_t is the amount of fluoride adsorbed per unit mass of adsorbent in mg/g at any time t. Concentration of 1 mg/L did not give a good fit to the model but other concentrations of 2 and 5 mg/L fitted moderately well into the model. The fittings into pseudo second-order kinetic models for different initial fluoride concentrations gave R^2 values between 0.68 and 0.93 to indicate that it was not the best fit model. The pseudo second-order rate constant k_2 and q_e

(calculated) values for each fluoride concentration from the slope and the intercept of the corresponding plots as listed in Table 8.4.

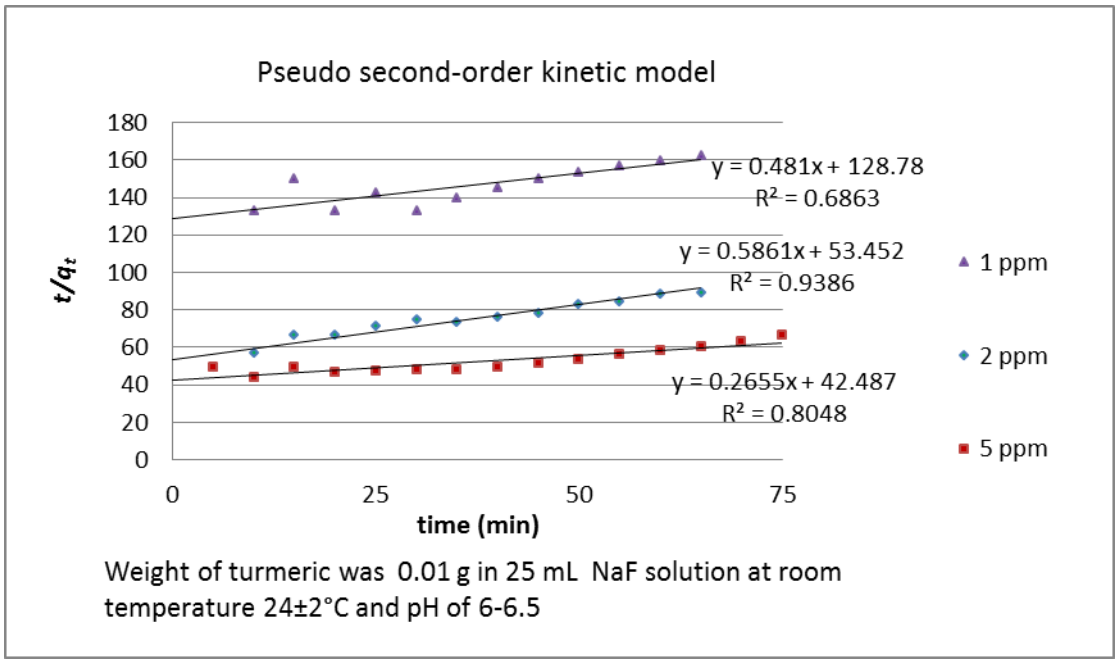


Figure 8.7 Adsorption results applied to pseudo second-order kinetic model

Table 8.4 Pseudo second-order kinetic model parameters for different fluoride concentrations

Fluoride concentration, mg/L	R^2	k_2 g/mg/min	q_e (cal) mg/g	q_e (expt) mg/g
1	0.6863	0.0184	2.053	0.675
2	0.9386	0.0064	1.706	0.975
5	0.8048	0.0016	3.773	1.425

(Weight of turmeric was 0.01 g in 25 mL fluoride solution at room temperature 24±2°C and pH of 6-6.5)

According to results it was observed that R^2 values were higher (0.994-0.996) for pseudo first-order kinetic model than pseudo second-order kinetic model (0.686-0.939). Also theoretical and experimental q_e values were in good agreement for pseudo first-order kinetic model. Therefore, it was suggested that the sorption of fluoride by turmeric powder followed the first-order kinetic model.

Intra-particle diffusion model was applied to experimental results to find out whether intra-particle diffusion was involved in fluoride adsorption on turmeric. Fluoride concentrations of 2 and 5 mg/L were fitted to Equation (5.11). When the amount of fluoride adsorbed per unit mass of adsorbent (q) was plotted as a function of square root of time ($t^{½}$), the fitted results

showed R^2 > 0.99 as shown in Figure 8.8. Intra-particle diffusion rate constant k_p (mg/g/min$^{1/2}$) calculations for fluoride concentrations 2 and 5 mg/L are given in Table 8.5.

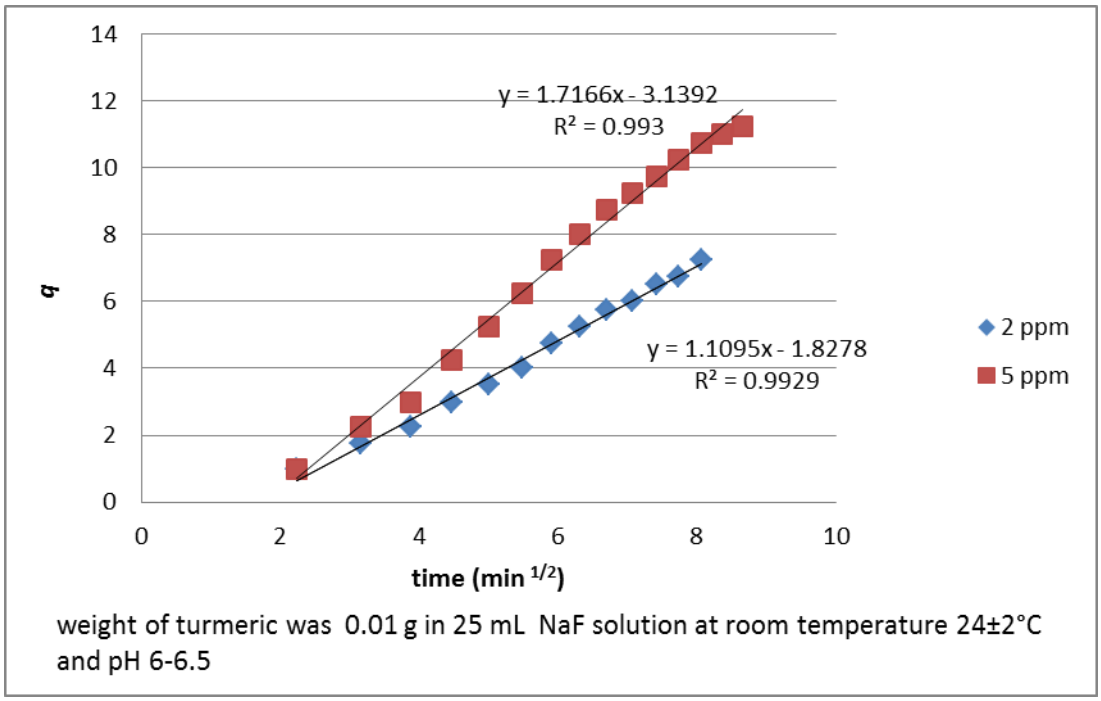


Figure 8.8 Intra-particle mass transfer model for adsorption of fluoride on turmeric

The plots in Figure 8.8 were curved initially but then linear at the end, indicated intra-particle diffusion effect governed by diffusion within the pores of the adsorbent. According to Intra-particle diffusion model, the first stage can be described as the initial accumulation of fluoride at a relatively larger area of adsorbent surface, and the slower second phase due to increasing occupation of surface binding sites as a feature of mono layer adsorption and desorption.

Table 8.5 Intra-particle diffusion rate constant for adsorption of fluoride on turmeric

Fluoride concentration, mg/L	R^2	k_p (mg/g.min $^{1/2}$)
2	0.992	1.109
5	0.993	1.716

8.2.3 The effect of temperature

The effect of temperature on fluoride removal was experimented and results are shown in Figure 8.9. Except temperature the other parameters were kept constant where initial

concentration of fluoride was 9 mg/L, pH = 6-6.5, volume of the sample = 25 mL, turmeric amount added to each sample = 0.01 g and stirring speed = 320 rpm. Fluoride removals at different temperatures were observed within 10 to 80 minutes time. The samples were monitored for removal of fluoride at temperatures 26±2°C and 30±2°C.

The results showed that fluoride adsorption (given by q_t as the fluoride amount adsorbed by adsorbent in mg/g) were higher at 30±2°C than at 26±2°C measured at 10, 15, 45 and 80 minutes. The effect of temperature is an important parameter as temperature is higher in Sri Lanka than lab experimental conditions. The CKD endemic areas are with an average temperature of 30°C. Therefore adsorption results showing higher adsorption at higher temperature were favourable for NCP of Sri Lanka.

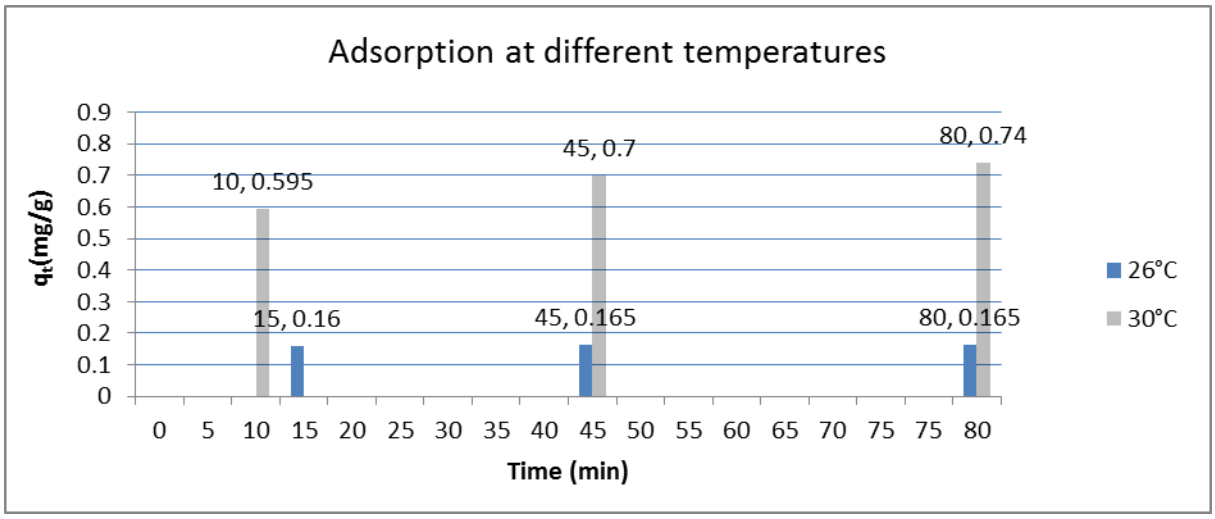


Figure 8.9 The effect of temperature on fluoride removal

8.2.4 The effect of pH of the solution

The effect of pH on fluoride adsorption over turmeric powder was studied for fluoride concentration at 9 mg/L, while other conditions were fixed as volume of the sample = 25 mL, turmeric dose = 0.01 g, stirring speed = 340 rpm and temperature of the solution 24±2°C. The pH values were varied as 3, 6.5, 9 and 10. Fluoride adsorbed per unit mass of adsorbent (q_e in mg/g) was monitored for each solution Figure 8.10. The results showed that adsorption was highest (q_e = 3.95 mg/g) at basic medium of pH = 10. Fluoride removal was not favourable at low pH. The probable reason for low adsorption in acidic condition is due

to hydroxyl ions which compete with fluoride ions in exchange sites. Also the distribution of fluoride ions which are controlled by pH of the aqueous solution could be another reason.

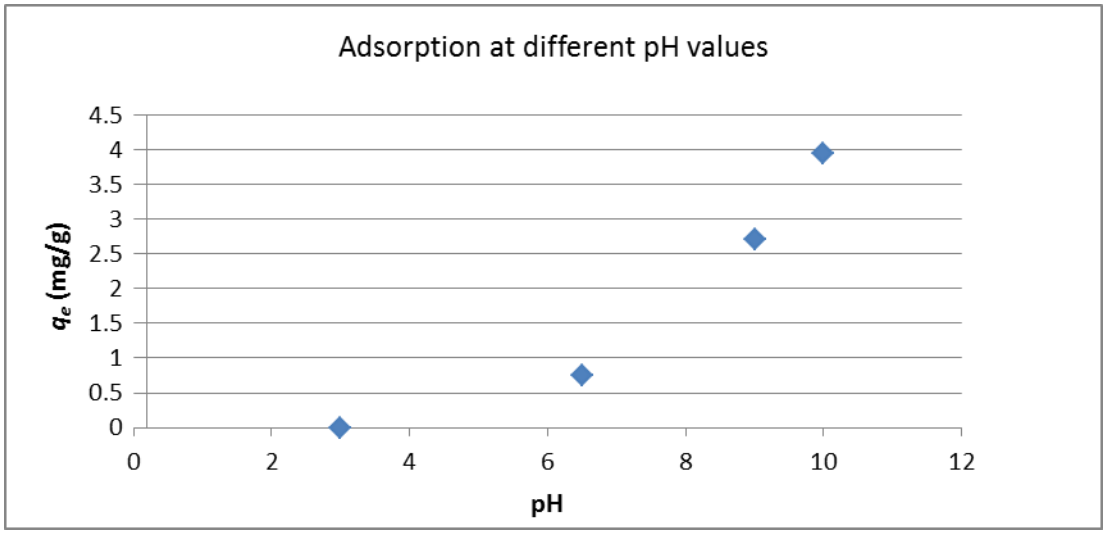


Figure 8.10 Effect of pH of the solution on fluoride removal

8.2.5 The effect of adsorbent dose

The effect of adsorbent dose on fluoride removal was investigated by keeping initial fluoride concentration at 10 mg/L. Varying turmeric doses experimented were 0.01, 0.04, 0.06 and 0.08 g, while other conditions were fixed at temperature 24±2°C, pH = 6-6.5 and stirring rate = 340 rpm. Fluorides adsorbed per unit mass of adsorbent (q_t in mg/g) at 25, 50 and 80 minutes are shown in Figure 8.11. It was observed that q_t was highest when the absorbent dosage was lowest at 0.01 g. This indicated that lower doses of turmeric were competing well to use all its available adsorption sites effectively to obtain a maximum adsorption capacity at a given fluoride concentration, temperature and pH of the solution.

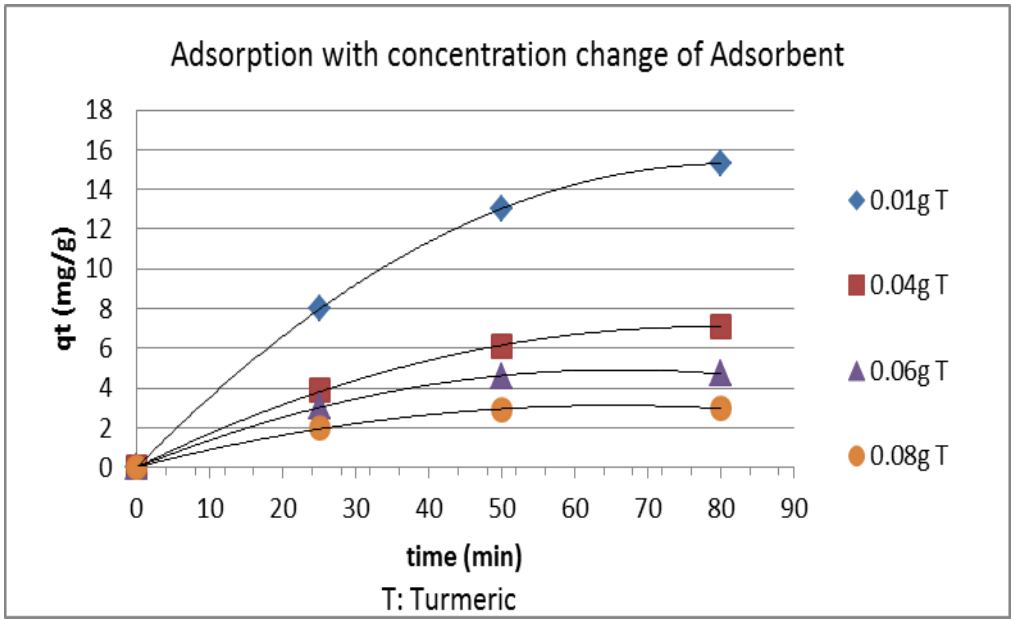


Figure 8.11 Effect of adsorbent dose on fluoride removal

8.3 Column experiment results

Column experiments were carried out to find out contact time necessary to achieve the equilibrium capacity in a fixed bed system. In fixed bed experiments fluoride solution (inlet solution) was added to a fixed bed (bed of known height) of turmeric powder continuously at a known flow rate and the outlet concentration (of fluoride leaving the bed) was measured with time. The outlet fluoride concentration was initially lower than the inlet fluoride concentration due to the reason that turmeric bed adsorbed fluoride. Once the bed adsorbed fluoride to the maximum capacity, the inlet and outlet fluoride concentrations became similar. The time taken for the effluent concentration to reach the influent concentration is called breakthrough time. Breakthrough curves were plotted using experimental results on C_t/C_0 against time where C_t is the outlet fluoride concentration at time t and C_o is the inlet concentration. At breakthrough, the outlet concentration C_t turned out to be similar to the inlet concentration C_o, therefore C_t/C_0 reached a value of 1. As such breakthrough time is the time for a column to reach C_t/C_0 equal to 1. With column experiments, process parameters namely inlet flow rate, initial fluoride concentration and bed height were studied.

8.3.1 Breakthrough analysis at different flow parameters

a) Effect of initial fluoride concentration

The effect of the four initial fluoride concentrations (e.g. 1.45, 2.45, 3.09 and 6.30 mg/L) on adsorption process at a constant flow rate of 0.33 mL/min and a fixed bed height of turmeric of 0.75 g weight were experimented. The results are shown in Figure 8.12.

The outlet concentrations of fluoride were measured in 14, 20, 28 and 30 minutes. The results showed breakthrough reached relatively faster at higher inlet fluoride concentrations due to quick saturation of the available adsorption sites. As such a plot of breakthrough times versus inlet concentrations gave a negative relationship as shown in Figure 8.13.

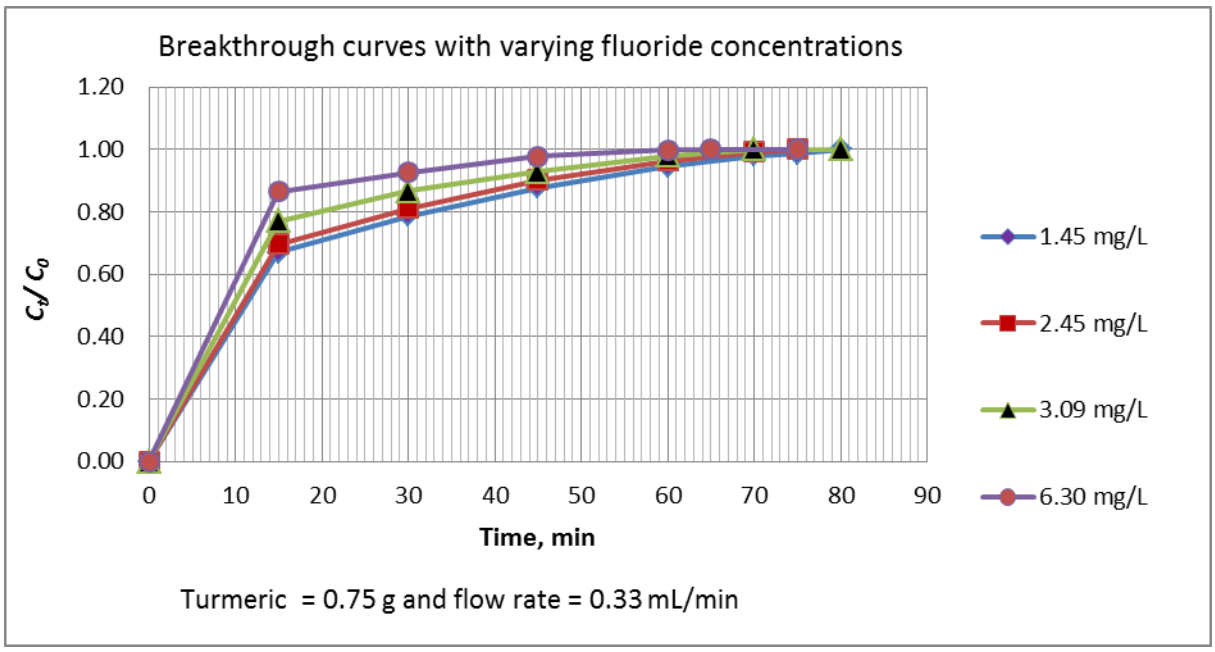


Figure 8.12 Breakthrough curves at varying initial concentrations of fluoride

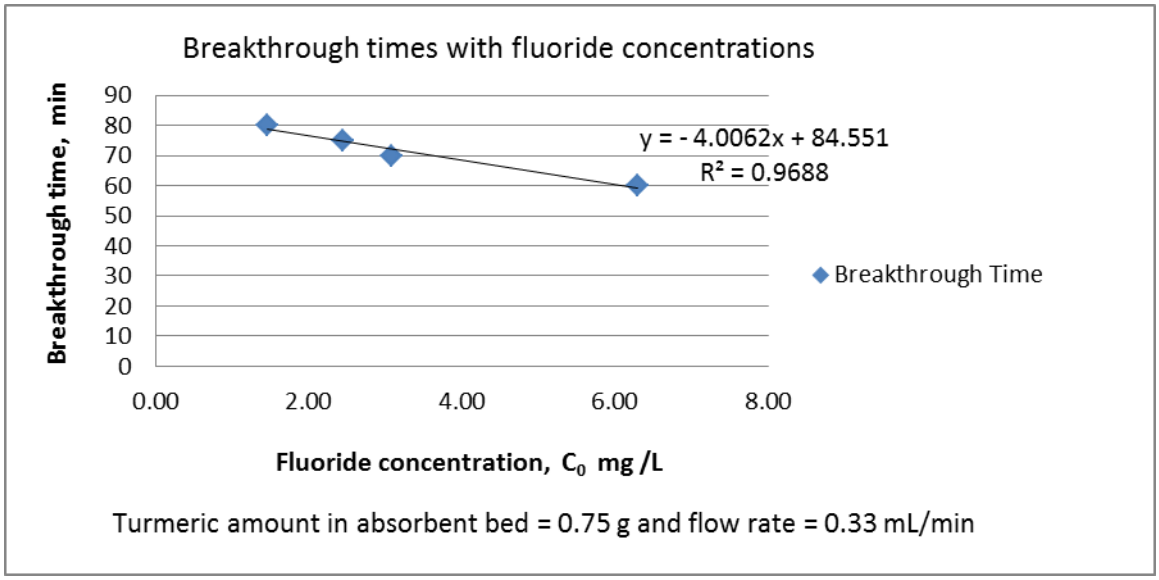


Figure 8.13 Relationship between breakthrough time and initial fluoride concentration

b) Effect of flow rate

Breakthrough curves of C_t/C_0 against time were estimated for various flow rates of 0.33, 0.66 and 0.99 mL/min at constant fluoride concentration of 3.09 mg/L and turmeric weight of 1.5 h in adsorbent bed. The results showed breakthrough to reach faster at higher flow rates (Figure 8.14). Also the breakthrough curves became steeper when the flow rate has increased to make breakpoint time requirement to be less. Han et al. (2009) have explained that increased flow rate causes a decrease in time in column adsorption. It was evident that increased flow rate caused a decrease in residence time (the time for fluoride solution to stay in turmeric bed), which in turn lowered the fluoride removal efficiency for a given column. With increased flow rate the fluoride ions had not enough time to diffuse into the pores of turmeric and left the bed before the equilibrium was reached. Thus, the contact time of fluoride ions with turmeric was shorter at higher flow rates. This was further represented by the breakthrough times for different flow rates in Figure 8.15.

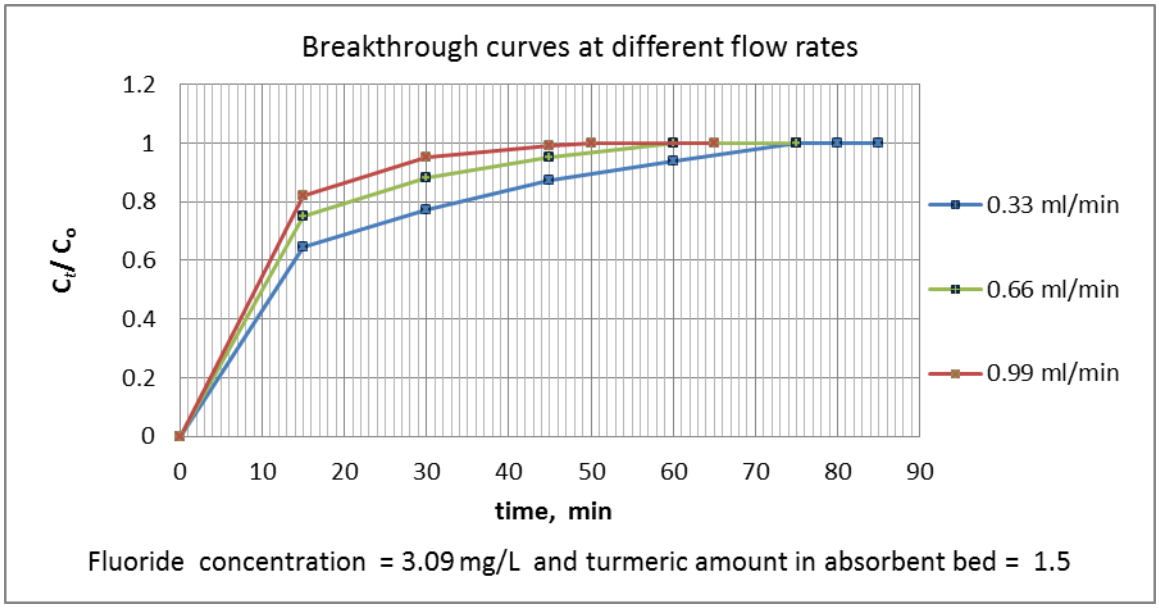


Figure 8.14 Breakthrough curves at varying flow rates

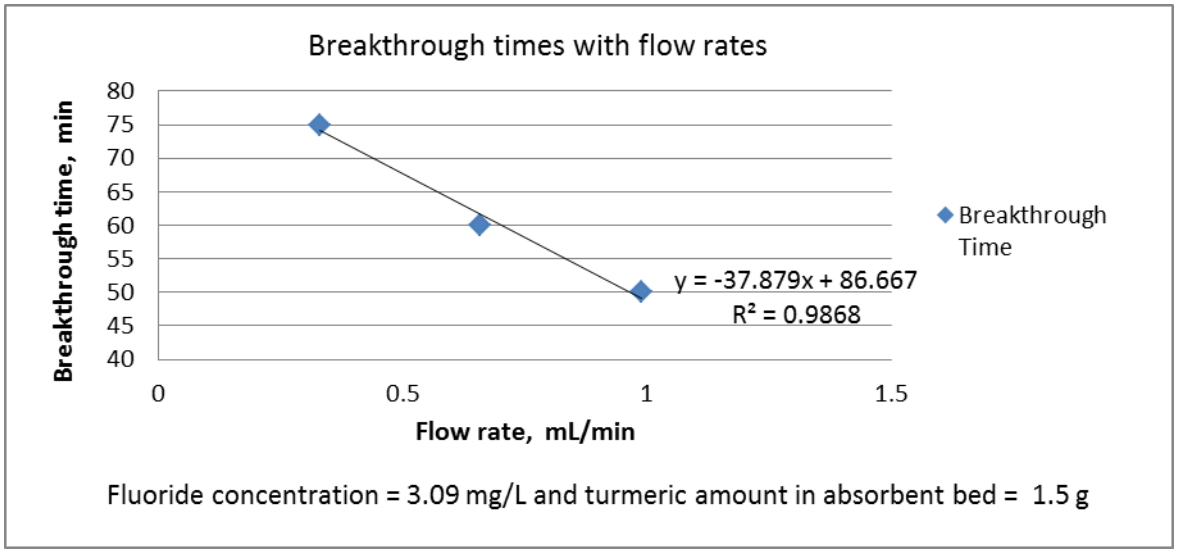


Figure 8.15 Relationship between breakthrough time and flow rate of the solution

c) Effect of bed height

The effect of the turmeric bed height on the adsorption process was experimented keeping flow rate and initial concentration of fluoride constant. The initial fluoride concentration was 3.09 mg/L and the flow rate was 0.33 mL/min. The bed heights were maintained at 0.5, 1.0 and 1.5 cm with turmeric weights of 0.75, 1.5 and 2.25 g, respectively. The breakthrough results showed a slower breakthrough with a higher bed height as shown in Figure 8.16. Breakthrough was reached faster by a smaller bed height due to quick saturation of the

available adsorption sites. On the other hand a higher bed height of adsorbent enabled more binding sites available for fluoride removal. Therefore, an increased bed height resulted in more contact time available for the fluoride to be with adsorbent as shown in Figure 8.17.

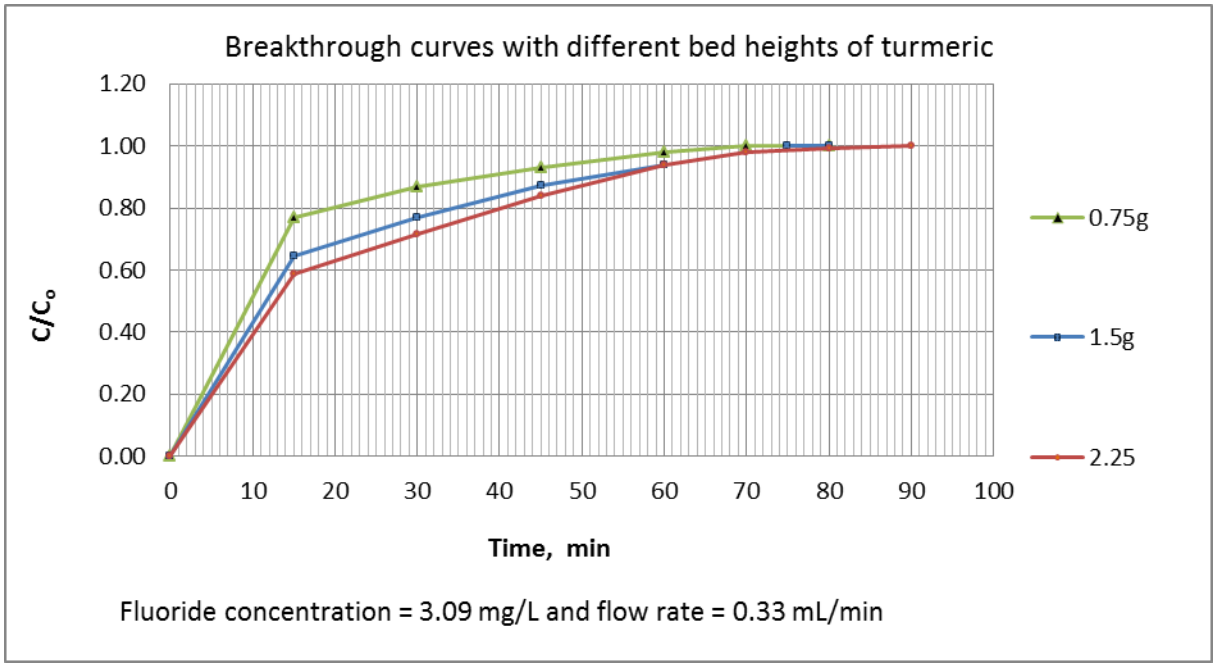


Figure 8.16 Breakthrough curves at varying bed heights (i.e. related to adsorbent weights)

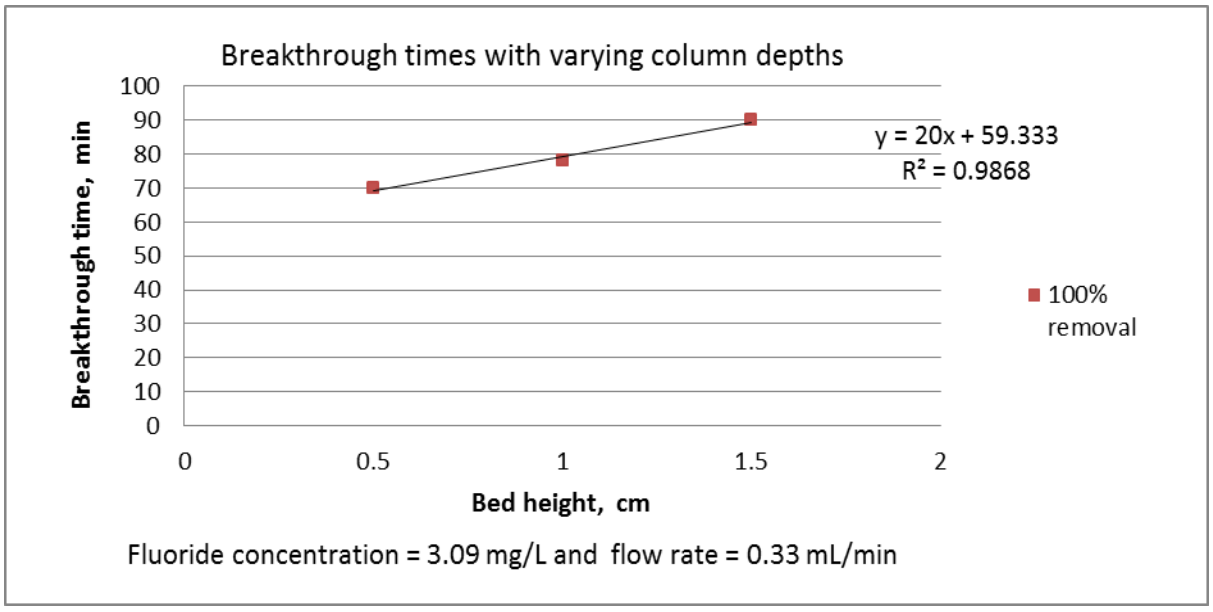


Figure 8.17 Relationship between breakthrough time and bed height of the adsorbent

8.3.2 Bed depth service time (BDST) model and critical bed depth calculation

When as adsorbate (fluoride) is applied to a given column of adsorbent (turmeric), bed depth service time (BDST) is the time required to reach a desired outlet concentration as a percentage of inlet concentration. BDST was calculated using fluoride solution having an initial concentration of 3.09 mg/L. To bring down this concentration to 1 mg/L (recommended level for consumption) it will be required to remove approximately 70% of fluoride from solution.

Using bed depths (column heights) of 0.5, 1.0 and 1.5 cm (with turmeric weights of 0.75, 1.5 and 2.25 g respectively) time required for 70% removal by each column was measured while other parameters were kept constant for all the beds including initial fluoride concentration = 3.09 mg/L and the flow rate = 0.33 mL/min. The linear flow velocity of influent to bed was calculated by dividing the flow rate (mL/min) by the column sectional area (cm^2). The column sectional area used in this experiment was 3.92 cm^2. Linear flow velocity of influent solution (V) was 0.07 cm/min.

The experimental results were plotted with break through times (t in minutes) against bed height (h in cm) as shown in Figure 8.18. The regression equations obtained in Figure 8.18 were used to calculate BDST model parameters according to Equation (5.13). As linear flow velocity of influent solution (V in cm/min) and initial concentration of solute (C_o in mg/L) were known, N_o, which was the adsorption capacity per unit volume of adsorbent column (mg/L) was calculated using the slope (m) and adsorption rate constant (k_a in L/mg/min) was calculated using the intercept of 70% removal line. The estimations for N_o and k_a are summarized in Table 8.6.

BDST model calculations using 70% removal of fluoride from 3.09 mg/L fluoride solution was also used to calculate the critical bed depth (h_o). This bed depth is defined as the height sufficient to ensure the outlet solute concentration does not exceed the breakthrough concentration (C_B) at time t = 0. The critical bed depth was calculated from Equation (5.14). N_o and k_a estimations done using 70% removal were used in critical bed depth (h_o) calculations. Initial concentration of solute (C_o) was 3.09 mg/L, and desired concentration of solute at breakthrough (C_B) was 1 mg/L. Then critical bed depth calculation (h_o) was approximately 0.33 cm (Table 8.6.)

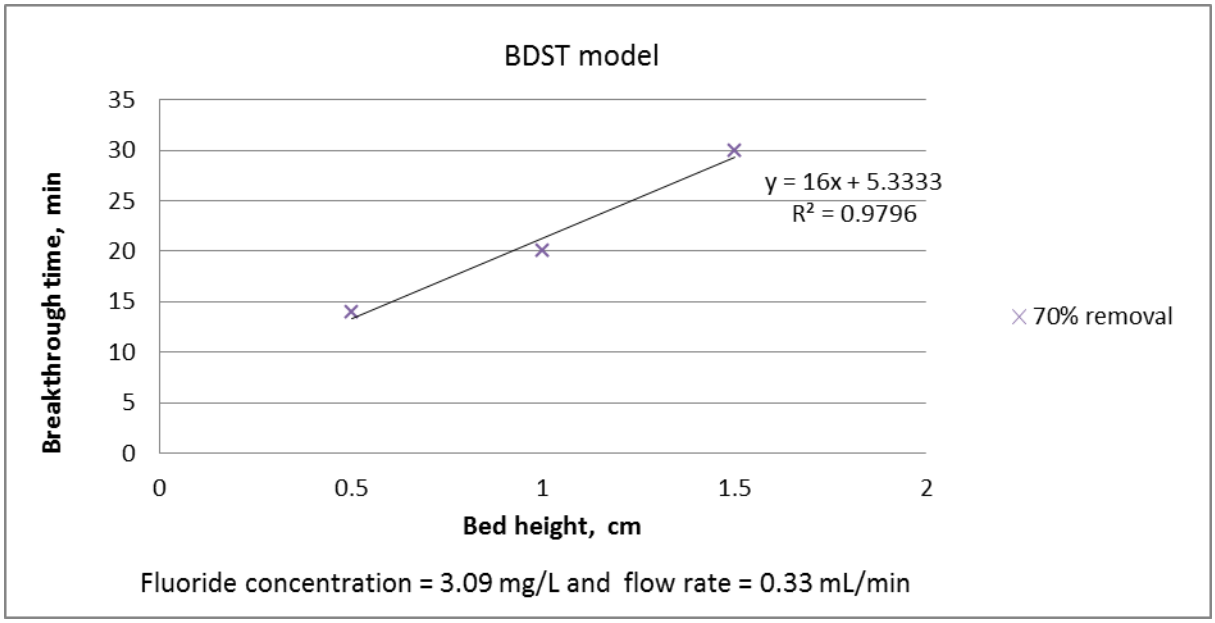


Figure 8.18 Relationships between breakthrough times and column depths

Table 8.6 Bed depth service time (BDST) parameters

C_o, mg/L	C_B, mg/L	Bed height (h), cm	Breakthrough time, min	k_a L/mg/min	N_o mg/L
3.09	0.93	0.5	15	0.51	3.312

8.3.3 Bohart-Adams model

The breakthrough results for 1.45, 2.45, 3.09 and 6.30 mg/L fluoride concentrations at varying flow rates and different bed heights were applied to Bohart-Adams model as expressed by Equation (5.15). The results are shown in Figures 8.19, 8.20 and 8.21, respectively. In the experiment, when initial fluoride concentration was varied other parameters like flow rate and bed height were kept constant. Same way when flow rate was varied, bed depth and fluoride concentration were kept constant; when bed depth was varied, fluoride concentration and flow rate were kept constant. Bohart-Adams parameter calculations are given in Table 8.7 where C_o = initial concentration of solute (mg/L), V = linear flow velocity of influent solution (cm/min), k_a = adsorption rate constant (L/mg/min) and N_o = adsorption capacity per unit volume of adsorbent column (mg/L) The linear flow velocity of influent to bed was calculated by dividing the flow rate (mL/min) by the column sectional area (cm^2). The column sectional area used in this experiment was 3.92 cm^2.

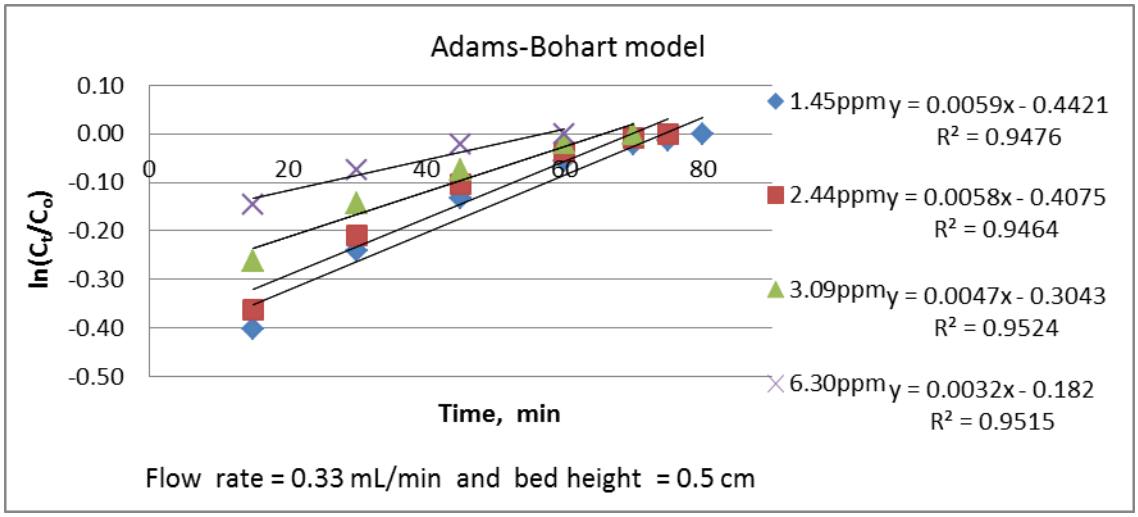


Figure 8.19 Application of Bohart-Adams model for varying fluoride concentrations

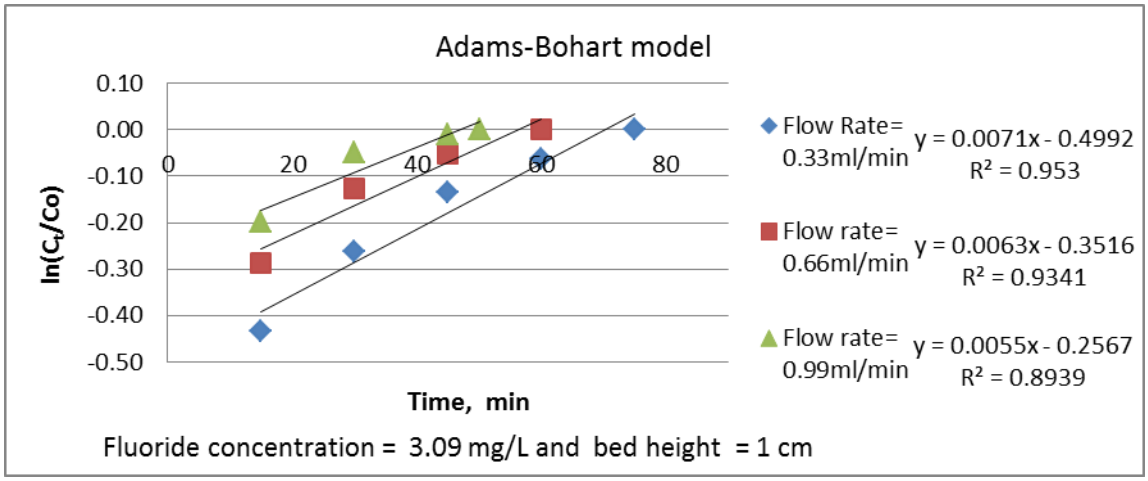


Figure 8.20 Application of Bohart-Adams model for varying flow rates

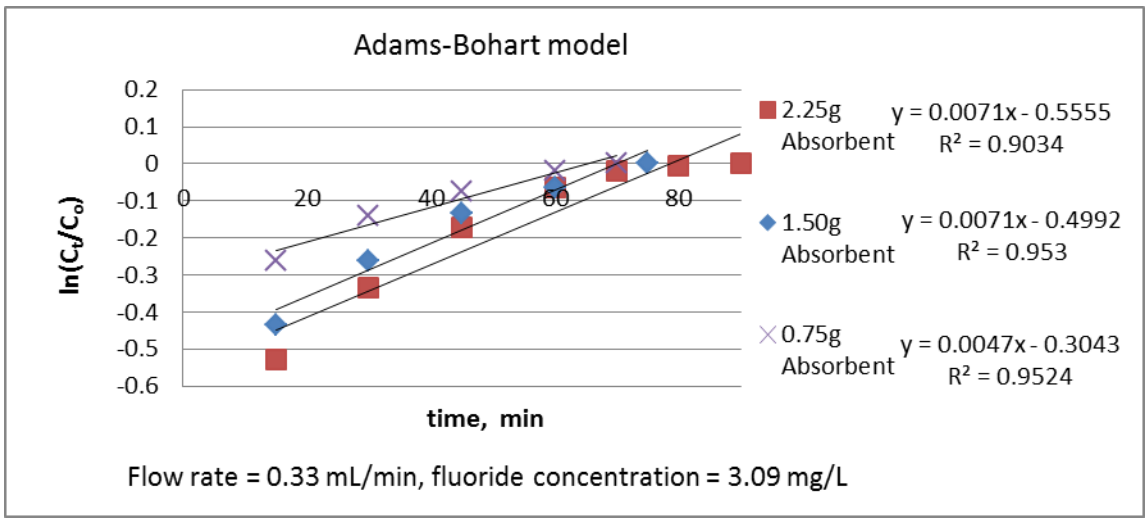


Figure 8.21 Application of Bohart-Adams model for varying bed depths

Table 8.7 Calculation of Bohart-Adams model parameters for varying adsorbate concentration, flow rates and bed heights

C_o mg/L	Flow rate, mL/min	V, cm/min	Bed height, cm	k_{AB}, mL/mg/minx10^4	N_o, mg/L	R^2
1.45	0.33	0.084	0.5	40.69	18.25	0.9476
2.44	0.33	0.084	0.5	23.77	28.80	0.9464
3.09	0.33	0.084	0.5	15.21	33.61	0.9524
6.30	0.33	0.084	0.5	5.08	60.20	0.9515
3.09	0.33	0.084	1.0	22.98	18.25	0.9530
3.09	0.66	0.170	1.0	20.39	29.32	0.9341
3.09	0.99	0.250	1.0	17.80	36.06	0.8939
3.09	0.33	0.084	1.5	22.98	13.54	0.9034
3.09	0.33	0.084	1.0	22.98	18.25	0.953
3.09	0.33	0.084	0.5	15.21	33.61	0.9524

The results indicated that k_{AB} values decreased when inlet concentration of fluoride and flow velocity have increased. On the other hand No values increased when bed depth, velocity and inlet concentration of adsorbent have increased to show a pattern in Figure 8.22,Figure 8.23, and Figure 8.24. Accoding to Aksu and Gönen (2004) the initial part of adsorption process is dominated by external mass transfer. As R^2 values showed a distribution between 0.89 and 0.95, the data fit into the model confirming Bohart-Adams model was suitable to explain the overall adsorption kinetics in the column experiments of fluoride removal using turmeric.

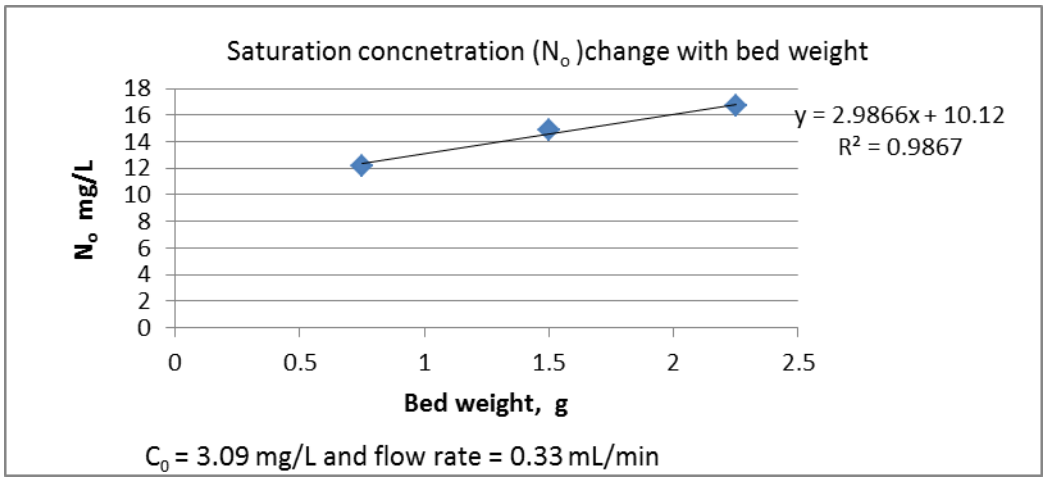


Figure 8.22 Saturation concentration (No) change with bed weight

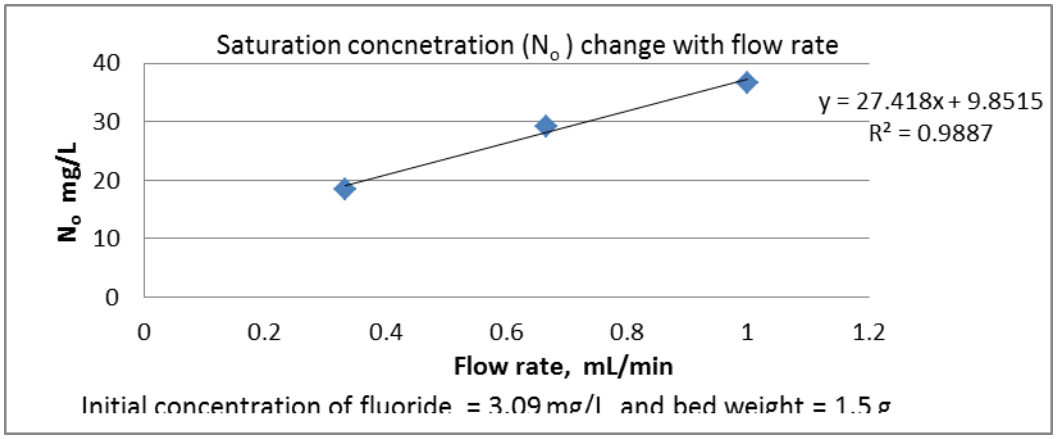


Figure 8.23 Saturation concentration (No) change with flow rate

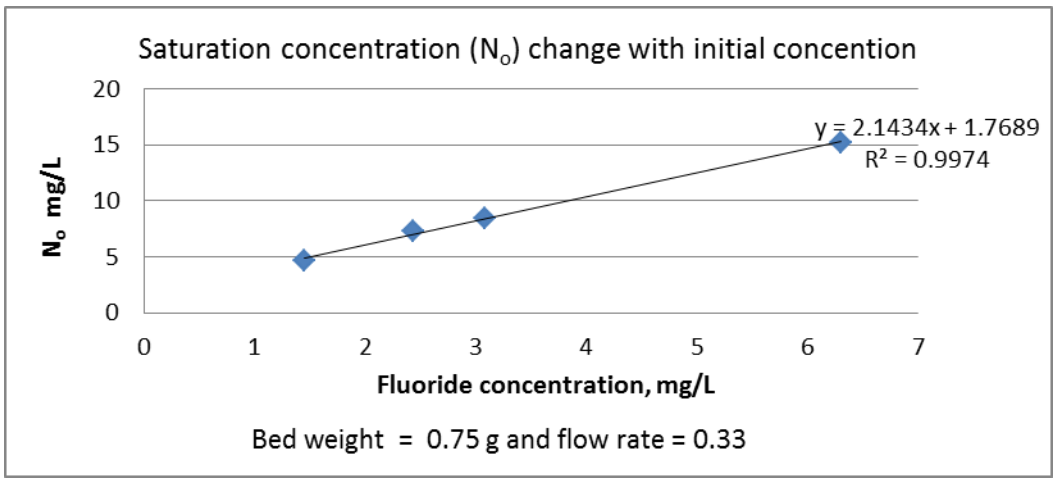


Figure 8.24 Saturation concentration (No) change with initial concentration

8.3.4 Thomas model

Column experimental results were plotted as shown in Figure 8.25 for Thomas model using Equation (5.16). In this equation W = mass of adsorbent used in the experiment (in g) and Q = inlet flow rate (mL/min). The values of q_e and k_{TH} were determined for different flow rates as shown in Table 8.8. When the experimental data were fitted to the Thomas model it was observed that the model parameters varied depending on flow rates. When the flow rate increased from 0.33 to 0.99 mL/min, k_{TH} value increased from 0.0146 to 0.032 mL/min/mg and the q_e decreased from 0.91 to 0.30 mg/g. The R^2 values were greater than 0.9, which validated the use of Thomas model to predict the maximum adsorption capacity of the bed.

Thomas model assumes Langmuir kinetics of adsorption-desorption on the assumption that the rate of driving force obeys second-order reversible reaction kinetics (Thomas 1944).

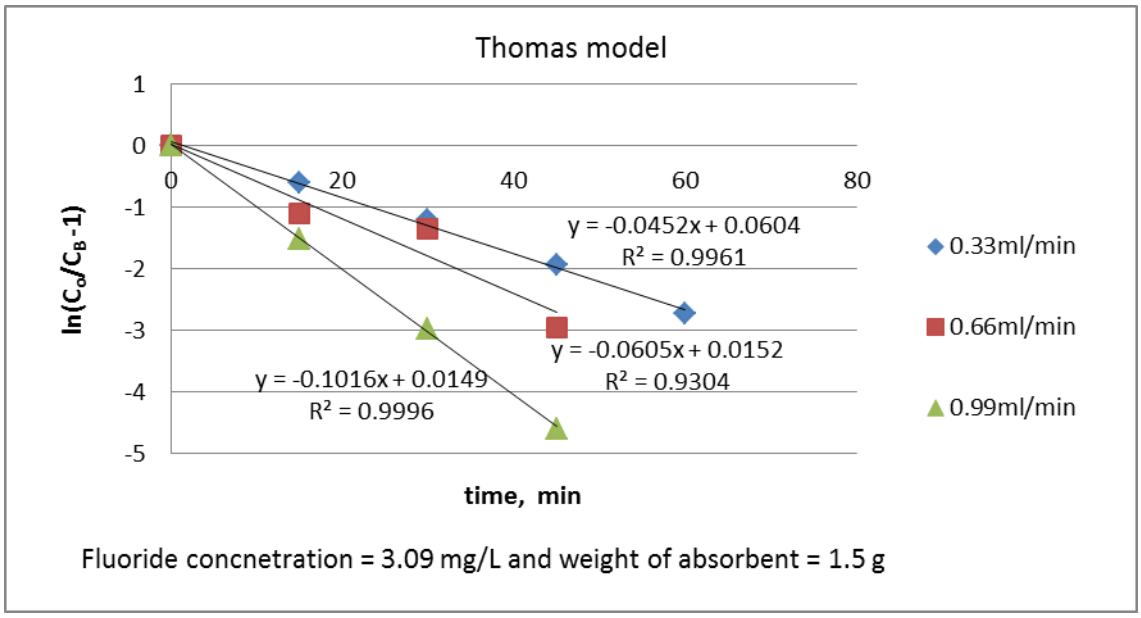


Figure 8.25 Application of Thomas model to calculate its parameters

Table 8.8 Calculation of Thomas model parameters for different flow rates

Flow rate, mL/min	q_e mg/g	k_{TH} mL/mg/min	R^2
0.33	0.910	0.0146	0.9961
0.66	0.343	0.0195	0.9304
0.99	0.300	0.0328	0.9996

8.4 Column regeneration studies

Columns with a bed of 0.75 g turmeric were subject to adsorption with 3.09 mg/L fluoride solution. All the regeneration studies were carried out at a flow rate of 0.33 mL/min to keep other parameters constant. These were flushed with 1.0M NaOH and 0.5M NaOH solutions. The regenerated columns were used for another cycle of adsorption using fluoride solutions of same concentration 3.09 mg/L. Adsorption capacity at equilibrium q_e (which is the amount of fluoride adsorbed per unit mass of adsorbent at equilibrium in mg/g) for normal turmeric powder and turmeric regenerated with 1.0M and 0.5M NaOH are given in Figure 8.26. The results showed that there were more regeneration with 1M NaOH than 0.5M NaOH but the adsorption capacity decreased after regeneration. Breakthrough time (in

minutes) for normal turmeric and turmeric regenerated with 1.0M and 0.5M NaOH are given in Figure 8.27. The time taken to reach breakthrough also decreased with regenerated turmeric. It was found that 1.0M NaOH was more effective than 0.5M NaOH in regenerating turmeric powder.

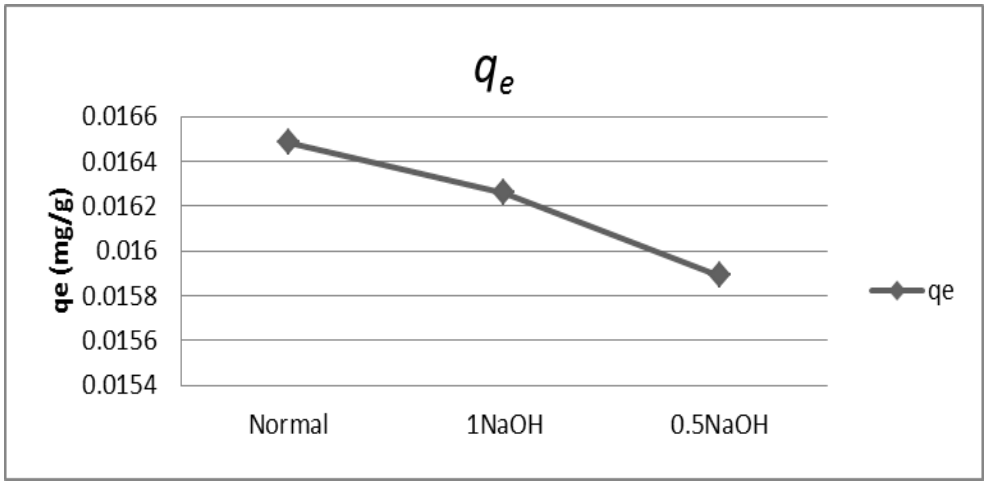


Figure 8.26 Regeneration of turmeric using different strength NaOH solutions

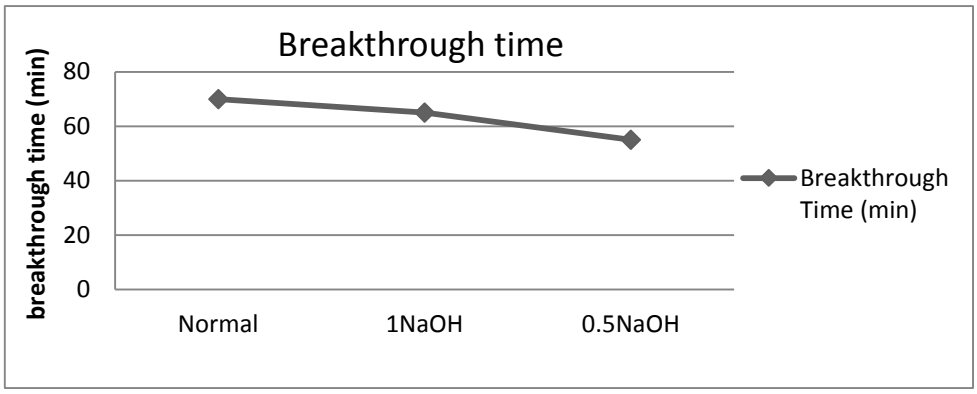


Figure 8.27 Breakthrough time before and after regeneration

8.5 Disposal of fluoride according to the environmental regulations in Sri Lanka

With regard to removal of fluoride and any other waste material associated with fluoride, the legislation applicable in Sri Lanka is the National Environment Act No. 47 of 1980 amended by Act No. 56 of 1988 and Act No. 53 of 2000. According to enactment of National Environment Act, there are limits by National Environmental Protection and Quality Regulations for the discharge of industrial wastes into inland surface waters which gives the

maximum tolerance limit of fluoride to be 2.0 mg/L. However the tolerance limit for industrial and domestic wastes discharged into marine coastal areas have a maximum limit of 15 mg/L for fluoride and tolerance limits for discharge of effluents into public sewers from central treatment plants to have a maximum limit of 20 mg/L for fluoride.

In CKD endemic areas of NCP there are no central treatment plants and the areas are away from coastal areas. As such the limit which applies to the area is 2 mg/L of fluoride to be discharged into inland surface water. According to the National Environmental Protection and Quality Regulations of Sri Lanka (No. 1 of 2008) any person who shall, discharge, deposit or emit waste into the environment or carry on any such prescribed activity should obtain an Environmental protection licence issued by the Central Environmental Authority (CEA) of Sri Lanka. The relevant Gazette notification of the Democratic Socialist Republic of Sri Lanka, dated February 1, 2008 states that "No person shall generate collect, transport, store, recover, recycle or dispose waste or establish any site or facility for the disposal of any waste specified in the Schedule VIII as scheduled waste except under the authority of a license issued by the CEA and in accordance with such standards and other criteria as may be specified by CEA".

8.6 Summary

Compared to Ginger and curry leaf powders turmeric powder was a better adsorbent for fluoride adsorption in water for average fluoride concentrations between 3 and 20 mg/L. The batch experiments revealed that removal of fluoride from aqueous solution was dependent on pH of the solution, adsorbent concentration and contact time. The removal of fluoride increased with the pH having a higher removal at pH more than 7. The influence of pH on adsorption was investigated as the pH range at household level in drinking water lies between 6 and 8.5 according to WHO standards. This indicated that it is preferable to carryout de-fluoridation at normal water pH and avoid acidic treatment. This is a better situation with regard to drinking water than many other natural adsorbents of fluoride as acidification is required, which is not required with turmeric.

The Freundlich and Langmuir adsorption models were used for the characterization of the fluoride adsorption on turmeric powder in batch experiments. Results showed that

adsorption equilibrium data fitted to the Langmuir adsorption isotherm indicating monolayer adsorption. They also followed Lagergen first order kinetic model which was indicative of physical adsorption of adsorbate molecules to turmeric than chemical adsorption described by pseudo second-order kinetic model.

The breakthrough curves of adsorption showed that adsorption was fast initially which slowed down with time showing breakthrough properties. The Bohart-Adams (or Wolborska) and Thomas models were applied to column experimental data obtained from dynamic studies performed on fixed columns to predict the breakthrough curves and to determine the column kinetic parameters. BDST model parameters were calculated and the same model parameters were used to predict the critical bed depth for fluoride which is necessary to prevent the effluent concentration exceeding inlet concentration.

The initial regions of breakthrough curves were defined by Bohart-Adams model. The variables selected were different flow rates and initial fluoride concentrations. The research results fitted to Bohart-Adams model. Desorption studies showed that turmeric can be reused for fluoride removal by rinsing fluoride adsorbed turmeric with NaOH. Higher concentrated (1.0M NaOH) was a better regenerator for turmeric than 0.5M NaOH. Total results revealed that turmeric has a potential for the removal of fluoride between 3 and 20 mg/L. At lower flow rates high percentage removal was observed indicating turmeric is a suitable adsorbent for fluoride removal in drinking water effectively at controlled flow rates.

9 CKD MINIMIZATION PLAN FOR NCP IN SRI LANKA

Excessive fluoride in groundwater used for drinking is a possible cause of CKD in NCP of Sri Lanka according to literature as well as the current research findings. Therefore uses of alternative sources for drinking purpose other than groundwater are options for mitigation of disease conditions in NCP. Alternate water sources include rainwater and other reservoir waters fed by rivers from the highland mountains. Although reservoir waters are found to be low in fluoride in the CKD endemic areas, these cannot be used for drinking purpose without full-scale treatment and disinfection. Water treatment facilities are not yet developed due to unaffordable financial conditions prevailing in the rural communities of the areas. Therefore, rainwater harvesting for potable use is proposed as a viable option at household level. In rainwater harvesting, lack of information about required tank capacities and unavailability of runoff surfaces were identified as limitations which were addressed herein. Reusable low-cost polythene sheet were proposed as runoff surfaces either over an existing roof or over a constructed simple frame. Polythene sheet is easy to handle and readily available in the market. Dimensionless graphs were prepared to enable any family to determine their tank sizes according to their demands. As estimated, the average tank sizes required for the area were between 3600 and 5700 L (for a four member family). The cost of an average sized brick-cement tank of 5000 L was estimated according to the 2013 prices given in Sri Lankan Rupees (SLR) as shown in Table 9.1.

Table 9.1 Brick-cement water tank estimation (according to the 2013 prices in Sri Lankan Rupees)

Description	Unit	Qty	Rate (SLR)	Cost (SLR)
Bricks (8 1/2" x3 3/4" x 2")	Nos	1225	9	11,025
Cement (50 kg bags)	Nos	12	1,000	12,000
Sand	m^3	1.35	3700	5,000
Random Rubble 6"/9"	m^3	0.59	1852	1,100
Metal (1")	m^3	0.27	1111	300
Mason	days	4	1,500	6,000
Helper	days	4	1,000	4,000
Sub-total				39,425
10% contingency				3,942
Total				**43,367**

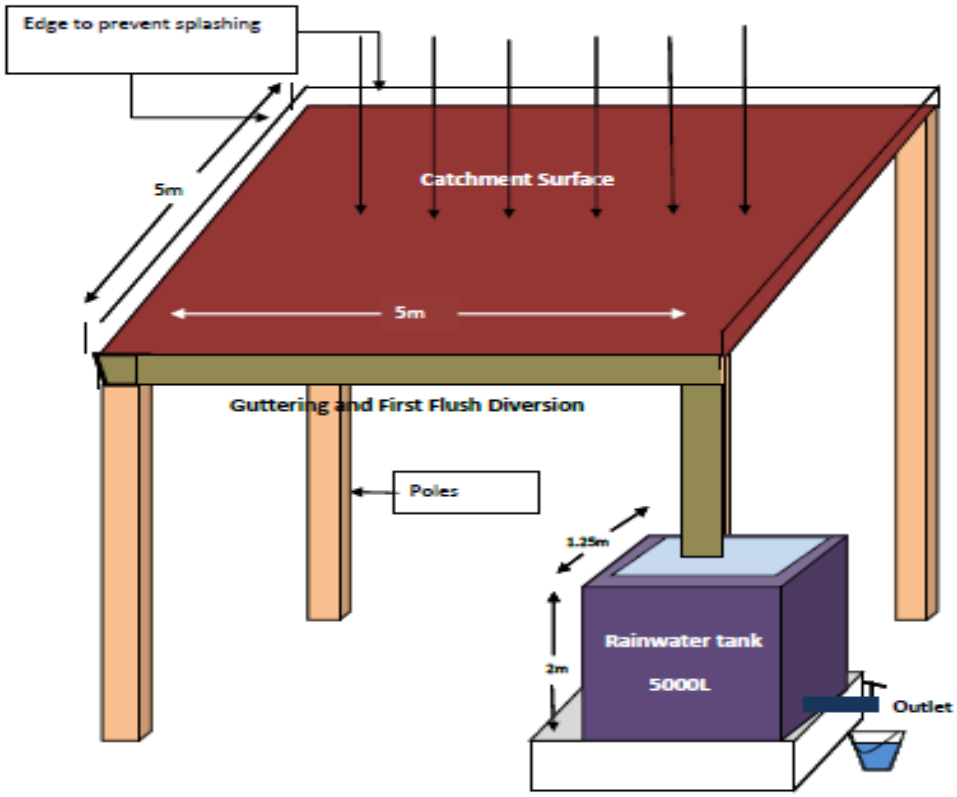


Figure 9.1 Proposed brick-cement water tank design with runoff surface in a simple frame

Alternatively in order to use available groundwater supplies, another option proposed in this research is to remove excess fluorides by adsorption. There are many advanced techniques for fluoride removal available in other countries but they are not feasible to the CKD affected areas of Sri Lanka due to poor economic status of the population. Therefore, some readily available natural food materials were investigated for fluoride removal. Out of them turmeric powder was found to have higher adsorption capacity than curry leaves and ginger. Therefore turmeric powder was further tested with batch and column experiments for fluoride removal characterization. A simple filter is proposed which can be applied by the people in the area at household level. A fixed bed process is proposed to be used in this filter made of turmeric powder, which is grown in household gardens of NCP. The advantages of a fixed bed system include little attention, easy inspection, cleaning and regeneration of the adsorbent material.

A simple fluoride removal filter using turmeric powder is shown in Figure 9.2. Accordingly the design consists of a main container where raw water is filled and has a tap to control the flow rate into the turmeric filter. The filter can be replaced or reused after cleaning. A cloth can hold the turmeric layer in the filter. The turmeric column depths need to be calculated according to the water flow and the amount of water to be filtered. BDST calculation can be used to determine the turmeric amount (height and area) required to adsorb fluoride. The second container stores the filtered water which is also fitted with a tap (outlet). These containers can be made out of clay or metal. They need to be placed at two levels as shown in Figure 9.2.

Apart from the above two main mitigation plans to prevent CKD in NCP, other sources of fluoride in food chain needs to be investigated and prevented. As many foods consumed in the CKD areas are found to contain excessive fluoride. Improving the nutritional status of the population at risk would also be considered as CKD minimization option. For example betel chewing with tobacco is a habit of farmer communities in the CKD area which is found to add fluoride to the diet of the community as discussed in the Literature Review chapter. Also the black tea consumed by farmers as a beverage in the area need to be reduced. Therefore, awareness of community about their food habits is also a concern in the control of CKD situation in NCP areas.

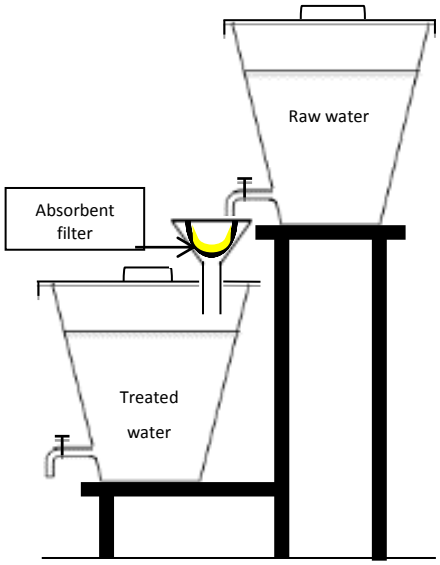


Figure 9.2 Proposed fluoride removal filter with turmeric as an adsorbent

10 CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

The purpose of this research was to investigate the causes of Chronic Kidney Disease (CKD) related to drinking water sources in North Central Province (NCP) of Sri Lanka. The research started with identifying the problem and setting out objectives. At this stage it was found that Anuradhapura and Polonnaruwa of NCP were the most affected districts in Sri Lanka. It was further identified that more than 85% of the drinking water requirements of the CKD endemic population were met by shallow wells. Impacts of high fluoride levels have been widely investigated in the literature. According to socioeconomic conditions and environmental evidences prevailing in NCP, it was hypothesised that drinking water could be the probable cause of CKD in the disease endemic areas. According to previous studies, the different assumptions undertaken on CKD occurrence in NCP were: elevated fluoride (F^-) content in drinking water; sodium (Na^+) to calcium (Ca^{2+}) ratio together with elevated fluoride levels in drinking water; use of aluminium utensils, which lead to aluminium and fluoride reactions in water to form aluminium fluoride (AlF_3); contamination of drinking water sources by cadmium (Cd^{2+}) and arsenic (As^{3-}) from inorganic fertilizer; and algae pollution of water bodies. This research is an in-depth investigation to find out water borne pollutants causing CKD in NCP of Sri Lanka. As such the research questions generated from the problem that need to be addressed were:

- What are the factors related to CKD in the disease endemic areas of Sri Lanka?
- How do those CKD causing factors arise in the disease endemic areas of Sri Lanka?
- How does CKD patient drinking water differ from CKD non-patients and why?
- What are the suitable harm minimisation techniques to control CKD?
- How can those harm minimisation techniques be applied to the CKD endemic areas in Sri Lanka?

An extensive literature review was carried out to perceive the recent and past studies on CKD. The results obtained from those literatures were utilised to identify the knowledge gap and thereby to conceptualize the framework of this study. At the inception of the study, a large number of drinking water samples were collected from Anuradhapura and Polonnaruwa CKD endemic areas. These samples were then classified as Anuradhapura

patient and non-patient, and Polonnaruwa patient and non-patient according to the field testing of patient and non-patient households. This approach eventually allowed the differentiation of causative factors by statistical methods of comparison. This set of primary data analysis was further supported by a set of secondary data source. Rainwater harvesting and removal of fluoride from drinking water were recommended as mitigation measures against CKD in the endemic areas of NCP. It also identified further work pertinent to the present problem and made recommendations for future research.

10.1.1 Statistical analysis

The five groups of water samples analysed were Anuradhapura patients and non-patients (ANU-P and ANU-NP), Polonnaruwa patients and non-patients (POL-P and POL-NP), and CKD-free control area Gampaha (GAM-C). According to descriptive statistical analysis, mean and median concentration levels of water parameters have not exceeded the WHO recommended values in any of the sampling groups. However there were incidences of fluoride levels of Anuradhapura patient sample exceeding the WHO standard. ANOVA and Kruskal-Wallis tests along with their post-hoc tests namely Dunnett's T3 and Mann-Whitney's tests results showed that Anuradhapura and Polonnaruwa patients and non-patients were significantly different due to significant differences in their average and median values of the variables. Secondary data from a published source was also analysed using the same analytical methods. It was found that the results of the secondary data were also consistent with the current research results.

When the water sampling data were analysed using Factorial Analysis, Anuradhapura patients showed the combination of fluoride and sodium factor with highest reliability than other factors, leading to believe the occurrence of sodium fluoride (NaF) in those CKD patients' samples. On the other hand the combination of fluoride and sodium was less reliable than fluoride and magnesium combination in Anuradhapura non-patient samples. In Polonnaruwa patient and non-patient samples, magnesium and fluoride factor leading to magnesium fluoride (MgF_2) was dominant. However in Polonnaruwa patient samples, it was found that sodium and fluoride as well as magnesium and fluoride combinations were almost similarly reliability. Fluoride and sodium factor combination could not be identified in Gampaha control area samples. These combination results can also be interpreted with

hydrogeology of the CKD endemic areas. Higher solubility of sodium fluoride (NaF) compared to MgF_2 and CaF_2 in groundwater can be the possible cause of higher sodium and fluoride correlation in patient water samples. The set of secondary data also indicated that the presence of CKD patients in the endemic area was associated with significant fluoride and sodium association. Furthermore secondary data suggested that fluoride levels in groundwater in CKD endemic areas were positively correlated with pH, sodium and alkalinity and negatively correlated with calcium and hardness. It was possible that leaching of fluoride-bearing minerals could enhance fluoride levels in NCP endemic samples.

Heavy metals like cadmium and arsenic were not found in Anuradhapura samples. In Polonnaruwa samples arsenic was not found but cadmium was found only in 3% of samples below WHO permissible level. Other heavy metals like iron, copper, zinc and lead levels in the CKD endemic samples were found with below WHO standard limits. Due to campaign against aluminium utensil use, people have completely given up the use of these utensils in the area.

Mean Na/Ca ratios in the CKD endemic areas were within the range between 1.6 and 6.6 according to Chandrajith et al. (2010b). This research results showed that CKD endemic area samples as well as control area Gampaha samples having the same ratio. As such Na/Ca ratio could not be used to differentiate between CKD endemic and non-endemic waters in this research.

Overall it was concluded that water quality issues cannot be generalised with average or median values of water parameters in identifying causes of CKD in the endemic areas of Sri Lanka. With the given series of statistical analysis, an in-depth analysis was conducted to identify water quality variations as well as all possible combinations of variables to identify the CKD causes in NCP of Sri Lanka.

10.1.2 Rainwater harvesting (RWH)

In developed countries, rainwater tank size calculations are carried out based on various simulation models which are not available in the CKD endemic areas of Sri Lanka. Therefore, this study was aimed to estimate rainwater tank sizes applicable to CKD endemic areas as one of the mitigation options. Optimum tank calculation ensured that the users would have

tank sizes adequate for potable water supply throughout the year, while expenses associated with oversized tanks could be avoided.

Mass curve method was applied to estimate required tank sizes using selected rainfall stations in Anuradhapura and Polonnaruwa endemic areas. The estimated tank sizes were between 3400 and 5100 L based on daily rainfall data and between 2900 and 5100 L based on monthly rainfall data. As such tank sizes based on daily rainfall were bigger than those based on monthly rainfall due to higher resolution in daily rainfall pattern (i.e. amount and frequency). Therefore estimations based on daily data were recommended. Minimum runoff surface area for each station was estimated based on the minimum hydrological year rainfall quantity. These estimations were more or less same for both monthly and daily rainfall data between 7 and 19 m^2. In some cases it was found that the calculated surface areas were not adequate when the demand and supply data were plotted to Mass curve graph due to the reason that the cumulative supply line fell below the cumulative demand line in a hydrological year. Therefore in such cases runoff surface areas were increased so that the minimum tank size can be achieved by having the minimum possible runoff surface areas. Cheap polythene material was proposed to be used as runoff surface.

Volumetric reliability of the estimated tank sizes were analysed for 60, 80 and 100% demand levels as percentages of average annual supply. Volumetric reliability varied depending on tank sizes and the graphs plotted can be used to determine the size of the tank that would be required for a family to supply water at a given reliability level.

Sensitivity analysis results showed that tank sizes were sensitive to runoff coefficient, household number and per capita consumption. The analysis showed that if runoff coefficient value was higher, smaller runoff surface area could serve a tank size and a smaller tank size could be compensated with a bigger runoff surface area.

According to the estimations, tank sizes were of manageable size and can be applied in Anuradhapura and Polonnaruwa at household levels to supply drinking water as an alternative to untreated groundwater supplies.

10.1.3 Use of natural adsorbent for fluoride removal

In In this study, an extensive laboratory investigation was carried out to evaluate batch and fixed-bed column performances using a natural adsorbent material which can be used cost effectively for fluoride removal in drinking water. Compared to ginger tuber and curry leaf powder, turmeric tuber powder was a better adsorbent for fluoride removal at normal pH range between 6 and 6.5.

The batch test results indicated that adsorption capacity increased with the initial fluoride concentration. It also revealed that adsorption increased with pH of the solution. Adsorption increased with temperature showing higher adsorption at 30±2°C compared to 24±2°C. Adsorption capacity of turmeric showed that fluoride adsorbed per unit mass of adsorbent (mg/g) was highest when the dosage was lowest at 0.01 g compared to 0.04, 0.06 and 0.08 g of adsorbent.

The adsorption of fluoride to turmeric powder best fitted to Langmuir isotherm, which is based on monolayer adsorption. Intra-particle mass transfer diffusion model indicated adsorption was also governed by diffusion. From the kinetic studies, it was found that fluoride removal by turmeric could be better described by pseudo first-order kinetic model indicating physical adsorption.

Column experimental data confirmed that adsorption of fluoride by turmeric is dependent on bed height (based on weight of the adsorbent loaded), inlet fluoride concentration and flow rate. The further results of this study were that both breakthrough time and exhaustion time increased with increasing bed height, but decreased with increasing fluoride concentration. Column experimental results were fitted to Bohart-Adams model (or Wolborska), Thomas model and BDST model. The initial region of breakthrough curve was defined by the Bohart-Adams model at all experimental conditions studied while the full description of breakthrough could be accomplished by the Thomas model.

Critical bed depth of turmeric powder required to bring down 3.09 mg/L fluoride to approximately 1 mg/L (around 70%) was also calculated using BDST model. Above model applications indicated that turmeric powder can be practically applied in fluoride filtration at column experimental conditions.

Turmeric was regenerated by 1.0M NaOH and 0.5M NaOH making the column ready for another sorption cycle. Adsorption capacity of regenerated turmeric was higher with 1.0M NaOH than 0.5M NaOH.

With adsorption results it was concluded that turmeric powder can be used as an adsorption material for removal of fluoride. Compared to other sophisticated fluoride removal methods, turmeric can be used as a cost-effective natural adsorbent in CKD endemic areas of Sri Lanka.

10.2 Recommendations

The following recommendations are proposed in this research:

As the current results were based on samples in the main CKD endemic areas of Anuradhapura and Polonnaruwa, it is recommended that the sampling be extended to other CKD prevailing areas in other districts.

It was found that family members consuming water from the same water wells were not equally affected by the disease. Therefore, it is recommended to do an in-depth study on other variables that could influence CKD such as age, gender and food habits of patients and non-patients.

One of the mitigation measures recommended was to use turmeric powder as a natural adsorbent for fluoride removal in drinking water. Further development of this method needs to be done to design an effective filter.

Finally, this study was limited to only an affected area in Sri Lanka, however future research can be used to identify similar CKD situations due to fluoride in groundwater in other parts of the world.

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ANNEXURES

Annexure 1. Factor analysis results: Anuradhapura patients

Descriptive Statistics

	Mean	Std. Deviation	Analysis N
Cl	81.7144	114.60799	102
F	.5236	.38540	102
N	1.1368	3.04406	102
P	.1817	.15330	102
Ca	61.2625	47.45267	102
Mg	27.8160	17.31783	102
Na	78.7767	68.63972	102

Correlation Matrix[a]

		Cl	F	N	P	Ca	Mg	Na
Correlation	Cl	1.000	.454	.391	.126	.771	.722	.798
	F	.454	1.000	.020	-.102	.417	.641	.597
	N	.391	.020	1.000	.802	.394	.263	.144
	P	.126	-.102	.802	1.000	.227	.143	-.026
	Ca	.771	.417	.394	.227	1.000	.787	.641
	Mg	.722	.641	.263	.143	.787	1.000	.667
	Na	.798	.597	.144	-.026	.641	.667	1.000
Sig. (1-tailed)	Cl		.000	.000	.103	.000	.000	.000
	F	.000		.422	.154	.000	.000	.000
	N	.000	.422		.000	.000	.004	.074
	P	.103	.154	.000		.011	.076	.398
	Ca	.000	.000	.000	.011		.000	.000
	Mg	.000	.000	.004	.076	.000		.000
	Na	.000	.000	.074	.398	.000	.000	

a. Determinant = .005

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.699
Bartlett's Test of Sphericity	Approx. Chi-Square	516.830
	df	21
	Sig.	.000

Communalities

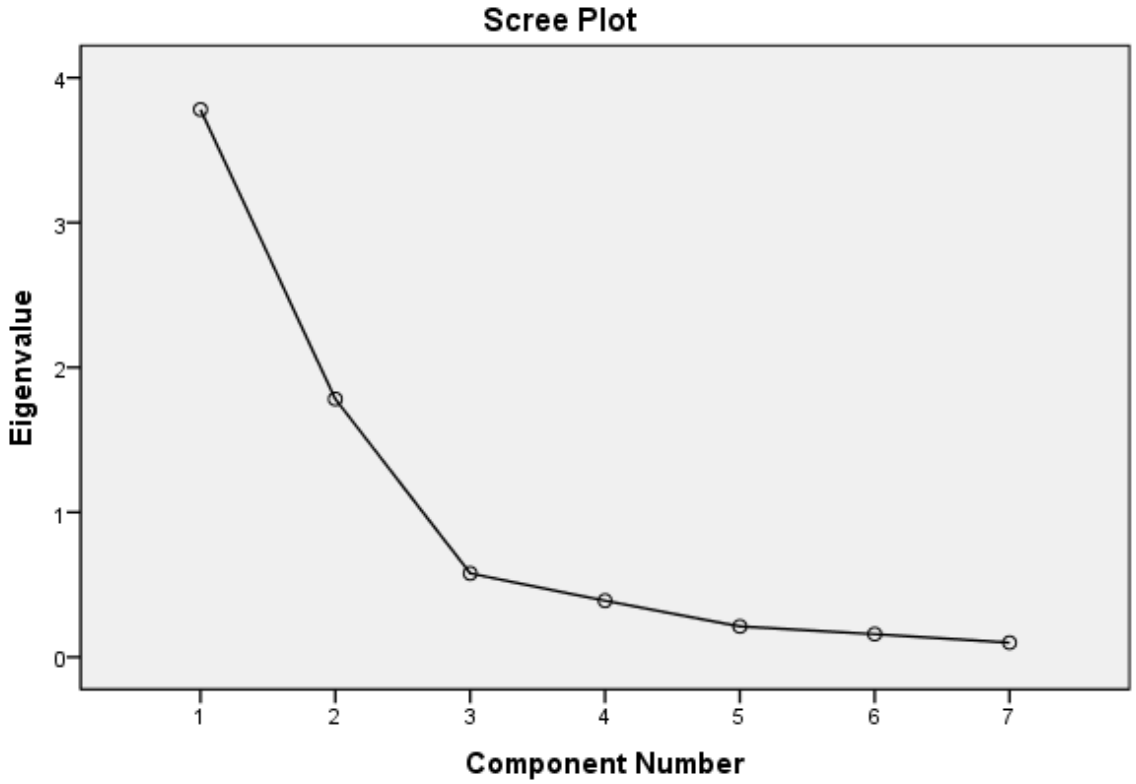
	Initial	Extraction
Cl	1.000	.808
F	1.000	.604
N	1.000	.898
P	1.000	.882
Ca	1.000	.775
Mg	1.000	.809
Na	1.000	.786

Extraction Method: Principal Component Analysis.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.781	54.009	54.009	3.781	54.009	54.009	3.598	51.403	51.403
2	1.782	25.453	79.462	1.782	25.453	79.462	1.964	28.059	79.462
3	.578	8.261	87.723						
4	.389	5.561	93.284						
5	.212	3.025	96.309						
6	.159	2.268	98.576						
7	.100	1.424	100.000						

Extraction Method: Principal Component Analysis.



Component Matrix[a]

	Component	
	1	2
Cl	.898	
Mg	.891	
Ca	.878	
Na	.837	
F	.657	-.415
P		.903
N	.458	.830

Extraction Method: Principal Component Analysis.

a. 2 components extracted.

Rotated Component Matrix[a]

	Component	
	1	2
Mg	.887	
Na	.886	
Cl	.868	
Ca	.820	
F	.752	
P		.939
N		.929

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.[a]

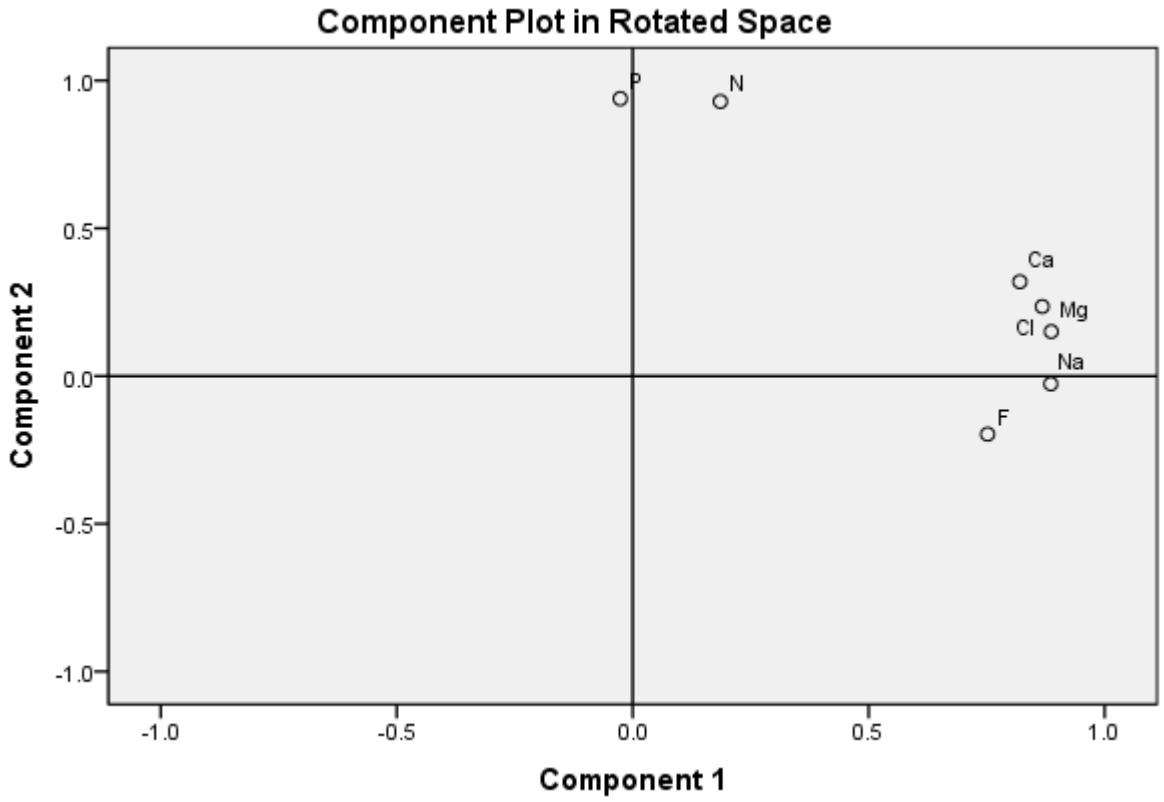
a. Rotation converged in 3 iterations.

Component Transformation Matrix

Component	1	2
1	.953	.302
2	-.302	.953

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.



Component Score Coefficient Matrix

	Component	
	1	2
Cl	.233	.051
F	.236	-.169
N	-.025	.481
P	-.088	.504
Ca	.212	.100
Mg	.246	.005
Na	.261	-.090

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

Component Score Covariance Matrix

Component	1	2
1	1.000	.000
2	.000	1.000

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

Scale Reliability Test: Factor 1

Case Processing Summary

		N	%
Cases	Valid	102	100.0
	Excluded[a]	0	.0
	Total	102	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.753	.903	5

Item Statistics

	Mean	Std. Deviation	N
Cl	81.7144	114.60799	102
F	.5236	.38540	102
Ca	61.2625	47.45267	102
Mg	27.8160	17.31783	102
Na	78.7767	68.63972	102

Inter-Item Correlation Matrix

	Cl	F	Ca	Mg	Na
Cl	1.000	.454	.771	.722	.798
F	.454	1.000	.417	.641	.597
Ca	.771	.417	1.000	.787	.641
Mg	.722	.641	.787	1.000	.667
Na	.798	.597	.641	.667	1.000

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
Cl	168.3787	14375.485	.867	.760	.660
F	249.5695	51250.733	.547	.519	.803
Ca	188.8307	35228.033	.778	.717	.647
Mg	222.2772	45291.750	.781	.749	.742
Na	171.3165	28291.466	.794	.706	.594

Scale Statistics

Mean	Variance	Std. Deviation	N of Items
250.0931	51346.418	226.59748	5

Scale Reliability Test: Factor 2

Case Processing Summary

		N	%
Cases	Valid	102	100.0
	Excluded[a]	0	.0
	Total	102	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.149	.890	2

Item Statistics

	Mean	Std. Deviation	N
N	1.1368	3.04406	102
P	.1817	.15330	102

Inter-Item Correlation Matrix

	N	P
N	1.000	.802
P	.802	1.000

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
N	.1817	.024	.802	.644	.
P	1.1368	9.266	.802	.644	.

Scale Statistics

Mean	Variance	Std. Deviation	N of Items
1.3185	10.039	3.16837	2

Annexure 2. Factor analysis results: Polonnaruwa patients

Descriptive Statistics

	Mean	Std. Deviation	Analysis N
Cl	48.7452	42.42364	90
F	.4917	.30058	90
N	1.8909	5.02944	90
P	.4439	.74019	90
Ca	69.4328	28.79673	90
Mg	28.6471	17.74293	90
Na	40.1721	23.17692	90

Correlation Matrix[a]

		Cl	F	N	P	Ca	Mg	Na
Correlation	Cl	1.000	.243	-.060	-.265	.633	.603	.689
	F	.243	1.000	.047	.025	.064	.562	.686
	N	-.060	.047	1.000	.716	.138	.293	.085
	P	-.265	.025	.716	1.000	-.170	-.102	-.134
	Ca	.633	.064	.138	-.170	1.000	.530	.321
	Mg	.603	.562	.293	-.102	.530	1.000	.830
	Na	.689	.686	.085	-.134	.321	.830	1.000
Sig. (1-tailed)	Cl		.010	.286	.006	.000	.000	.000
	F	.010		.330	.409	.274	.000	.000
	N	.286	.330		.000	.098	.003	.212
	P	.006	.409	.000		.055	.169	.104
	Ca	.000	.274	.098	.055		.000	.001
	Mg	.000	.000	.003	.169	.000		.000
	Na	.000	.000	.212	.104	.001	.000	

a. Determinant = .007

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.543
Bartlett's Test of Sphericity	Approx. Chi-Square	426.219
	df	21
	Sig.	.000

Communalities

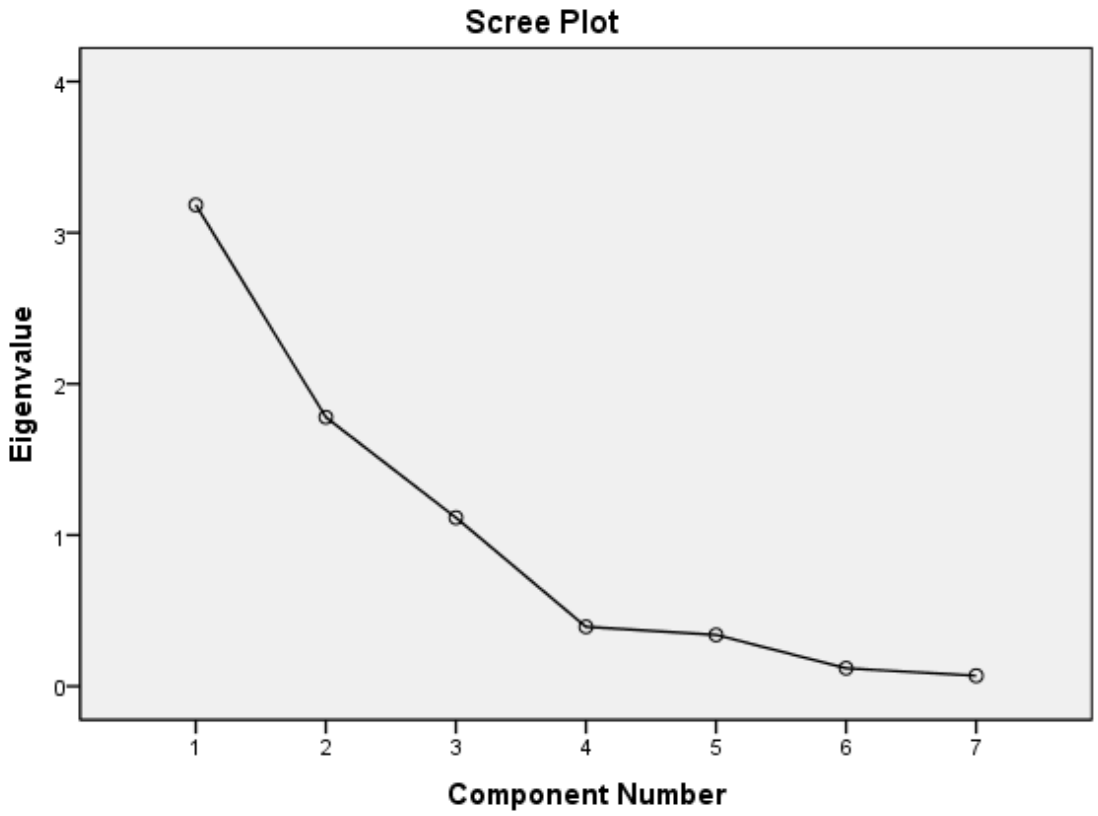
	Initial	Extraction
Cl	1.000	.803
F	1.000	.866
N	1.000	.914
P	1.000	.867
Ca	1.000	.852
Mg	1.000	.863
Na	1.000	.913

Extraction Method: Principal Component Analysis.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.184	45.486	45.486	3.184	45.486	45.486	2.243	32.047	32.047
2	1.780	25.422	70.908	1.780	25.422	70.908	2.078	29.679	61.726
3	1.115	15.930	86.838	1.115	15.930	86.838	1.758	25.112	86.838
4	.393	5.613	92.451						
5	.340	4.855	97.306						
6	.119	1.704	99.010						
7	.069	.990	100.000						

Extraction Method: Principal Component Analysis.



Component Matrix[a]

	Component		
	1	2	3
Mg	.913		
Na	.912		
Cl	.814		
N		.917	
P		.910	
Ca	.633		.667
F	.631		-.664

Extraction Method: Principal Component Analysis.

a. 3 components extracted.

Rotated Component Matrix[a]

	Component		
	1	2	3
F	.928		
Na	.862	.410	
Mg	.708	.586	
Ca		.922	
Cl		.797	
N			.942
P			.903

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.[a]

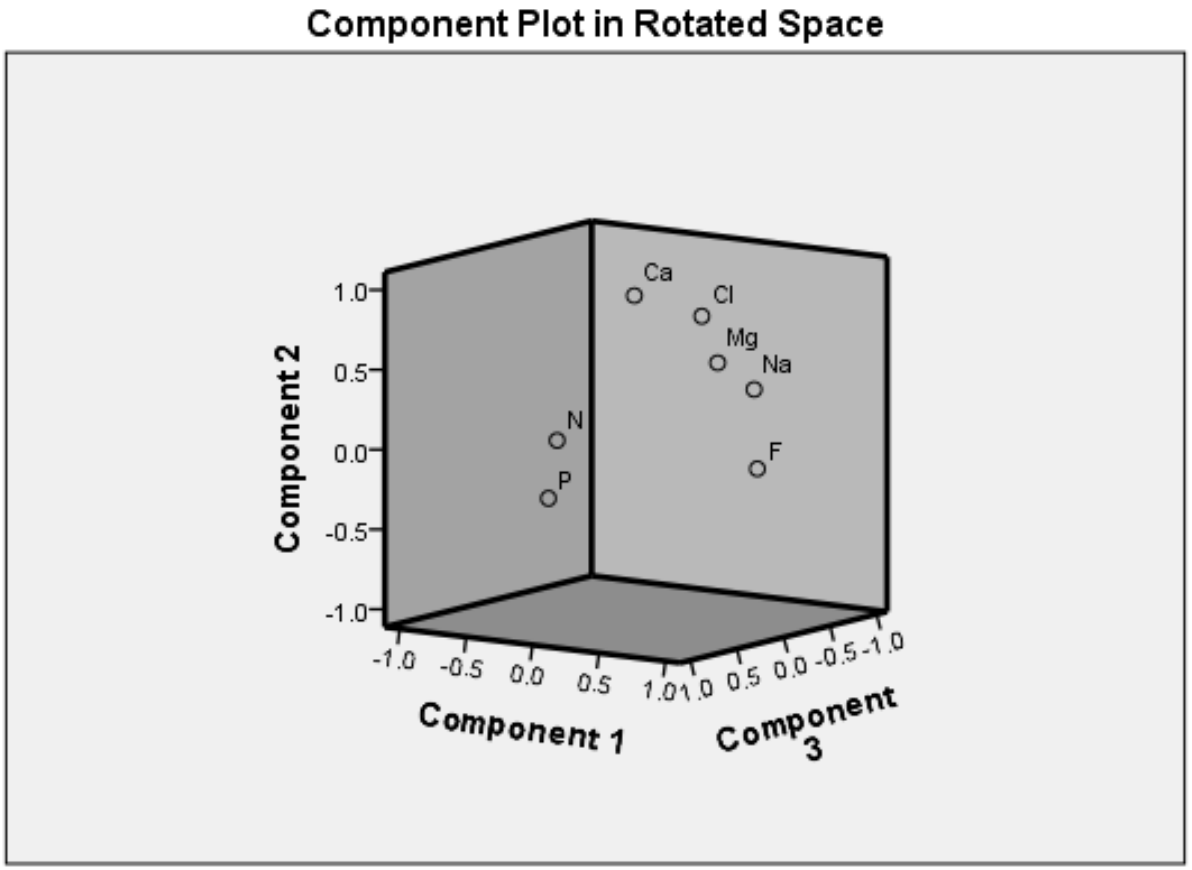
a. Rotation converged in 4 iterations.

Component Transformation Matrix

Component	1	2	3
1	.734	.679	-.029
2	.147	-.117	.982
3	-.663	.725	.185

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.



Component Score Coefficient Matrix

	Component		
	1	2	3
Cl	-.010	.384	-.080
F	.554	-.308	-.025
N	-.039	.123	.545
P	.017	-.088	.507
Ca	-.257	.574	.065
Mg	.236	.171	.080
Na	.381	.009	-.032

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

Component Score Covariance Matrix

Component	1	2	3
1	1.000	.000	.000
2	.000	1.000	.000
3	.000	.000	1.000

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

Scale Reliability Test: Factor 1

Case Processing Summary

		N	%
Cases	Valid	90	100.0
	Excluded[a]	0	.0
	Total	90	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.675	.871	3

Item Statistics

	Mean	Std. Deviation	N
F	.4917	.30058	90
Na	40.1721	23.17692	90
Mg	28.6471	17.74293	90

Inter-Item Correlation Matrix

	F	Na	Mg
F	1.000	.686	.562
Na	.686	1.000	.830
Mg	.562	.830	1.000

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
F	68.8192	1534.324	.660	.471	.889
Na	29.1388	320.896	.833	.759	.037
Mg	40.6638	546.819	.830	.688	.035

Scale Statistics

Mean	Variance	Std. Deviation	N of Items
69.3109	1549.966	39.36961	3

Scale Reliability Test: Factor 2

Case Processing Summary

		N	%
Cases	Valid	90	100.0
	Excluded[a]	0	.0
	Total	90	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.741	.775	2

Item Statistics

	Mean	Std. Deviation	N
Cl	48.7452	42.42364	90
Ca	69.4328	28.79673	90

Inter-Item Correlation Matrix

	Cl	Ca
Cl	1.000	.633
Ca	.633	1.000

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
Cl	69.4328	829.252	.633	.400	.
Ca	48.7452	1799.765	.633	.400	.

Scale Statistics

Mean	Variance	Std. Deviation	N of Items
118.1780	4175.032	64.61449	2

Scale Reliability Test: Factor 3

Case Processing Summary

		N	%
Cases	Valid	90	100.0
	Excluded[a]	0	.0
	Total	90	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.342	.834	2

Item Statistics

	Mean	Std. Deviation	N
N	1.8909	5.02944	90
P	.4439	.74019	90

Inter-Item Correlation Matrix

	N	P
N	1.000	.716
P	.716	1.000

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
N	.4439	.548	.716	.512	.
P	1.8909	25.295	.716	.512	.

Scale Statistics

Mean	Variance	Std. Deviation	N of Items
2.3348	31.173	5.58324	2

Annexure 3. Factor analysis results: Anuradhapura non-patients

Descriptive Statistics

	Mean	Std. Deviation	Analysis N
Cl	112.8750	81.60455	60
F	.3878	.28323	60
N	3.7319	4.90772	60
P	.1788	.12670	60
Ca	66.8057	38.19063	60
Mg	31.0113	19.06390	60
Na	79.1742	39.16739	60

Correlation Matrix[a]

		Cl	F	N	P	Ca	Mg	Na
Correlation	Cl	1.000	.139	.449	-.190	.668	.861	.341
	F	.139	1.000	-.034	-.137	.475	.232	.159
	N	.449	-.034	1.000	-.327	.726	.475	-.345
	P	-.190	-.137	-.327	1.000	-.454	-.288	.182
	Ca	.668	.475	.726	-.454	1.000	.751	-.057
	Mg	.861	.232	.475	-.288	.751	1.000	.458
	Na	.341	.159	-.345	.182	-.057	.458	1.000
Sig. (1-tailed)	Cl		.144	.000	.073	.000	.000	.004
	F	.144		.398	.149	.000	.037	.113
	N	.000	.398		.005	.000	.000	.003
	P	.073	.149	.005		.000	.013	.082
	Ca	.000	.000	.000	.000		.000	.331
	Mg	.000	.037	.000	.013	.000		.000
	Na	.004	.113	.003	.082	.331	.000	

a. Determinant = .004

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.552
Bartlett's Test of Sphericity	Approx. Chi-Square	311.619
	df	21
	Sig.	.000

Communalities

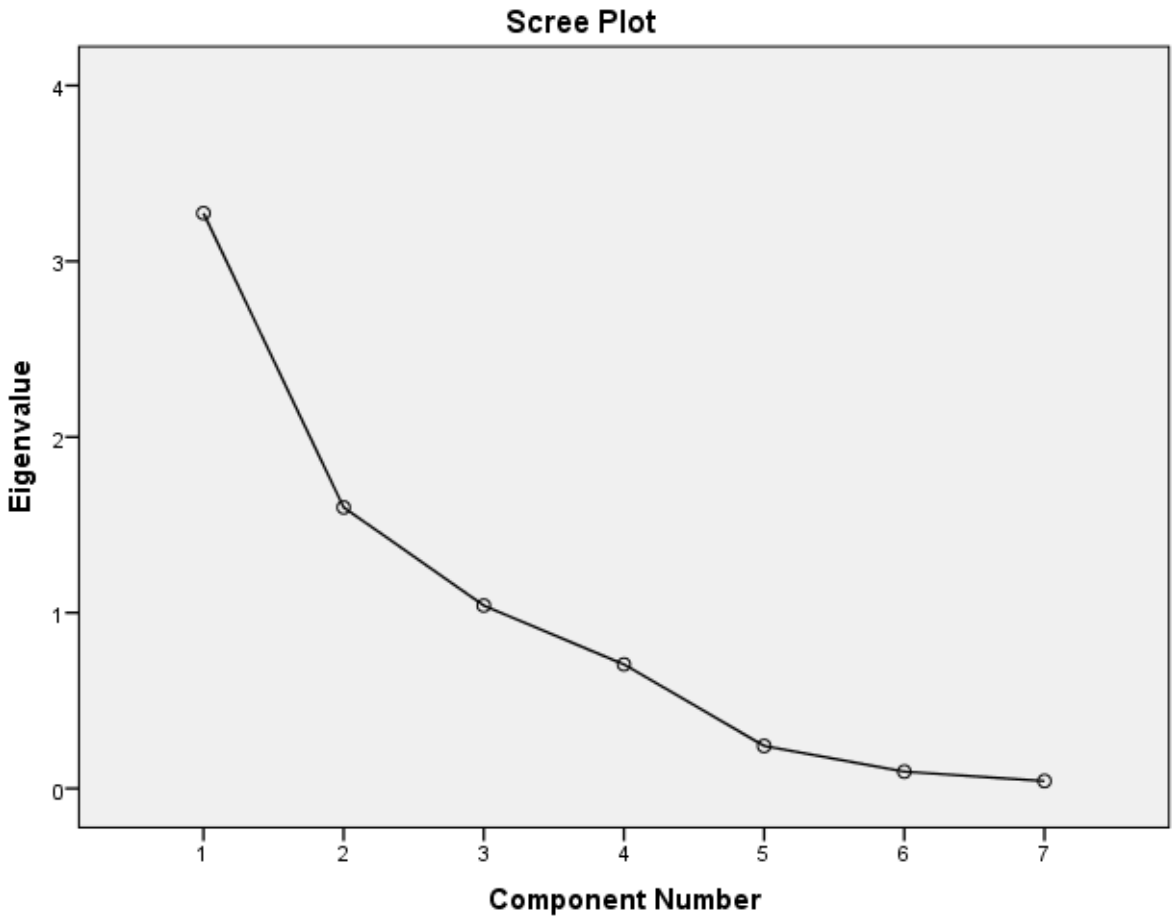
	Initial	Extraction
Cl	1.000	.872
F	1.000	.931
N	1.000	.853
P	1.000	.483
Ca	1.000	.939
Mg	1.000	.950
Na	1.000	.886

Extraction Method: Principal Component Analysis.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.274	46.766	46.766	3.274	46.766	46.766	2.760	39.423	39.423
2	1.599	22.850	69.616	1.599	22.850	69.616	1.907	27.248	66.671
3	1.041	14.868	84.484	1.041	14.868	84.484	1.247	17.813	84.484
4	.706	10.086	94.569						
5	.242	3.459	98.029						
6	.096	1.368	99.397						
7	.042	.603	100.000						

Extraction Method: Principal Component Analysis.



Component Matrix[a]

	Component		
	1	2	3
Ca	.935		
Mg	.904		
Cl	.842		
N	.691	-.545	
P	-.480	.430	
Na		.924	
F			-.865

Extraction Method: Principal Component Analysis.

a. 3 components extracted.

Rotated Component Matrix[a]

	Component		
	1	2	3
Mg	.957		
Cl	.929		
Ca	.669	.583	
N	.478	.771	
Na	.521	-.764	
P		-.610	
F			.960

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.[a]

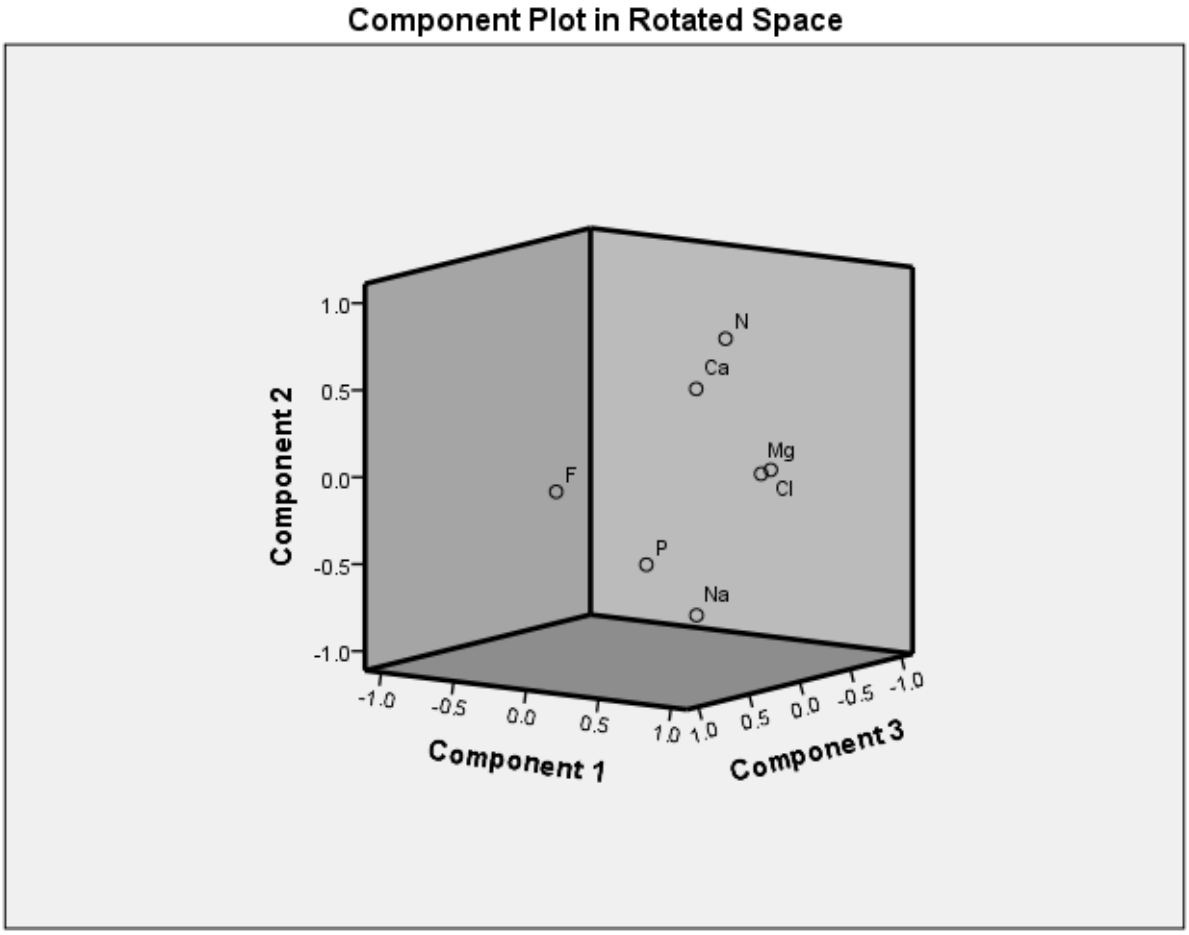
a. Rotation converged in 5 iterations.

Component Transformation Matrix

Component	1	2	3
1	.856	.430	.287
2	.385	-.901	.201
3	.345	-.062	-.937

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.



Component Score Coefficient Matrix

	Component		
	1	2	3
Cl	.384	-.065	-.152
F	-.138	-.022	.838
N	.142	.381	-.258
P	.065	-.321	-.223
Ca	.143	.239	.211
Mg	.371	-.071	-.037
Na	.287	-.502	.074

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

Component Score Covariance Matrix

Component	1	2	3
1	1.000	.000	.000
2	.000	1.000	.000
3	.000	.000	1.000

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

Scale Reliability Test: Factor 1

Case Processing Summary

		N	%
Cases	Valid	60	100.0
	Excluded[a]	0	.0
	Total	60	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.725	.905	3

Item Statistics

	Mean	Std. Deviation	N
Mg	31.0113	19.06390	60
Cl	112.8750	81.60455	60
Ca	66.8057	38.19063	60

Inter-Item Correlation Matrix

	Mg	Cl	Ca
Mg	1.000	.861	.751
Cl	.861	1.000	.668
Ca	.751	.668	1.000

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
Mg	179.6807	12282.623	.893	.797	.678
Cl	97.8170	2914.959	.777	.743	.750
Ca	143.8863	9703.095	.699	.565	.552

Scale Statistics

Mean	Variance	Std. Deviation	N of Items
210.6920	16419.417	128.13827	3

Scale Reliability Test: Factor 2

Case Processing Summary

		N	%
Cases	Valid	60	100.0
	Excluded[a]	0	.0
	Total	60	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha[a]	Cronbach's Alpha Based on Standardized Items[a]	N of Items
-.138	-.729	3

a. The value is negative due to a negative average covariance among items. This violates reliability model assumptions. You may want to check item codings.

Item Statistics

	Mean	Std. Deviation	N
N	3.7319	4.90772	60
Na	79.1742	39.16739	60
P	.1788	.12670	60

Inter-Item Correlation Matrix

	N	Na	P
N	1.000	-.345	-.327
Na	-.345	1.000	.182
P	-.327	.182	1.000

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
N	79.3531	1535.908	-.346	.192	.002
Na	3.9107	23.695	-.343	.125	-.034[a]
P	82.9061	1425.430	.146	.113	-.186[a]

a. The value is negative due to a negative average covariance among items. This violates reliability model assumptions. You may want to check item codings.

Scale Statistics

Mean	Variance	Std. Deviation	N of Items
83.0849	1426.847	37.77362	3

Annexure 4. Factor analysis results: Polonnaruwa non-patients

Descriptive Statistics

	Mean	Std. Deviation	Analysis N
Cl	30.5065	21.51442	60
F	.4795	.27075	60
N	.1682	.21209	60
P	.0847	.11187	60
Ca	60.3062	19.06873	60
Mg	22.0322	12.81583	60
Na	33.6003	20.99469	60

Correlation Matrix[a]

		Cl	F	N	P	Ca	Mg	Na
Correlation	Cl	1.000	.506	.231	.297	.466	.670	.634
	F	.506	1.000	-.141	.129	.573	.794	.710
	N	.231	-.141	1.000	.328	-.138	.042	.054
	P	.297	.129	.328	1.000	.164	.186	.172
	Ca	.466	.573	-.138	.164	1.000	.704	.414
	Mg	.670	.794	.042	.186	.704	1.000	.749
	Na	.634	.710	.054	.172	.414	.749	1.000
Sig. (1-tailed)	Cl		.000	.038	.011	.000	.000	.000
	F	.000		.141	.162	.000	.000	.000
	N	.038	.141		.005	.146	.376	.341
	P	.011	.162	.005		.106	.078	.094
	Ca	.000	.000	.146	.106		.000	.000
	Mg	.000	.000	.376	.078	.000		.000
	Na	.000	.000	.341	.094	.000	.000	

a. Determinant = .023

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.770
Bartlett's Test of Sphericity	Approx. Chi-Square	211.030
	df	21
	Sig.	.000

Communalities

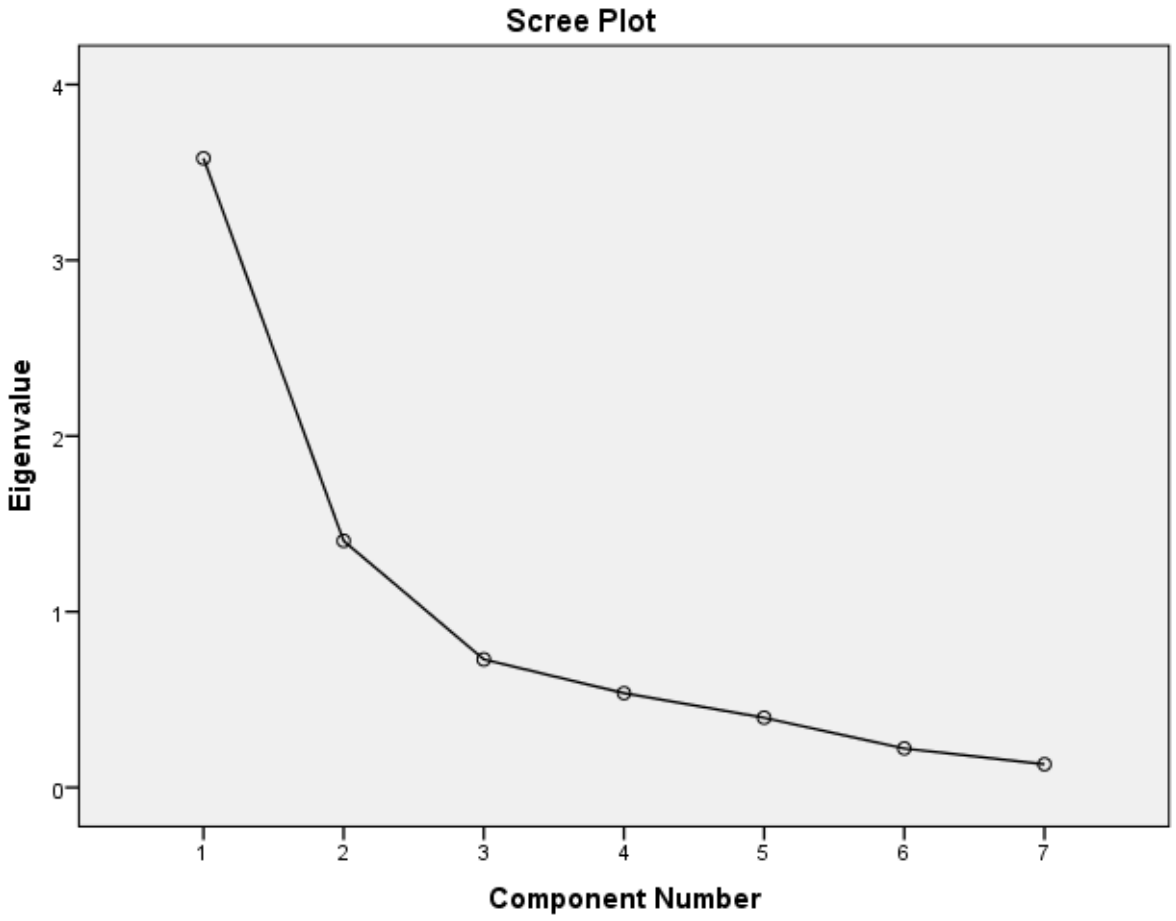
	Initial	Extraction
Cl	1.000	.695
F	1.000	.790
N	1.000	.749
P	1.000	.561
Ca	1.000	.598
Mg	1.000	.883
Na	1.000	.708

Extraction Method: Principal Component Analysis.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.581	51.153	51.153	3.581	51.153	51.153	3.499	49.979	49.979
2	1.403	20.044	71.197	1.403	20.044	71.197	1.485	21.218	71.197
3	.729	10.413	81.610						
4	.537	7.668	89.278						
5	.397	5.669	94.946						
6	.222	3.168	98.114						
7	.132	1.886	100.000						

Extraction Method: Principal Component Analysis.



Component Matrix[a]

	Component	
	1	2
Mg	.936	
F	.851	
Na	.841	
Cl	.791	
Ca	.739	
N		.864
P		.681

Extraction Method: Principal Component Analysis.

a. 2 components extracted.

Rotated Component Matrix[a]

	Component	
	1	2
Mg	.934	
F	.885	
Na	.827	
Ca	.769	
Cl	.725	.412
N		.858
P		.729

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.[a]

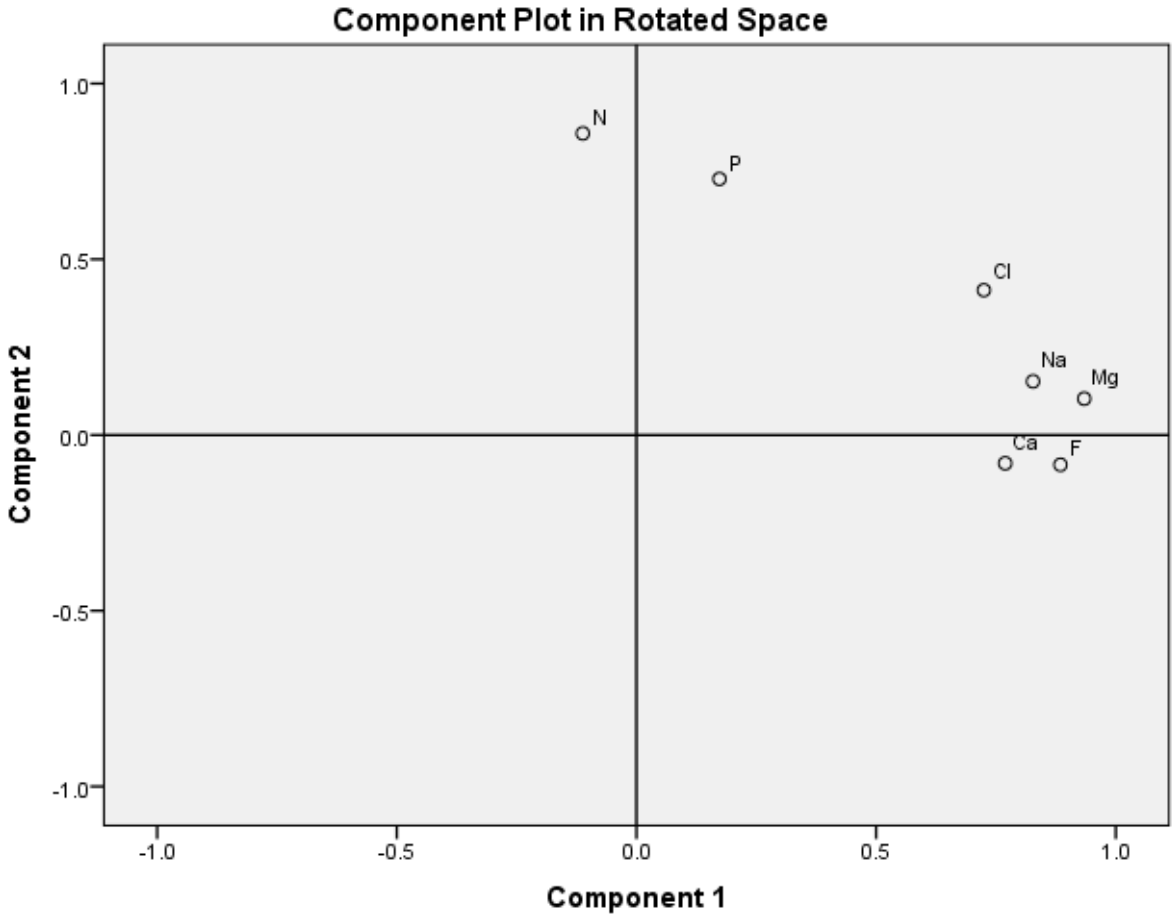
a. Rotation converged in 3 iterations.

Component Transformation Matrix

Component	1	2
1	.981	.194
2	-.194	.981

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.



Component Score Coefficient Matrix

	Component	
	1	2
Cl	.180	.227
F	.268	-.132
N	-.104	.607
P	-.009	.493
Ca	.234	-.120
Mg	.268	-.005
Na	.232	.038

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

Component Score Covariance Matrix

Component	1	2
1	1.000	.000
2	.000	1.000

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

Scale Reliability Test: Factor 1

Case Processing Summary

		N	%
Cases	Valid	60	100.0
	Excluded[a]	0	.0
	Total	60	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.786	.892	5

Item Statistics

	Mean	Std. Deviation	N
Cl	30.5065	21.51442	60
F	.4795	.27075	60
Ca	60.3062	19.06873	60
Mg	22.0322	12.81583	60
Na	33.6003	20.99469	60

Inter-Item Correlation Matrix

	Cl	F	Ca	Mg	Na
Cl	1.000	.506	.466	.670	.634
F	.506	1.000	.573	.794	.710
Ca	.466	.573	1.000	.704	.414
Mg	.670	.794	.704	1.000	.749
Na	.634	.710	.414	.749	1.000

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
Cl	116.4182	2067.086	.680	.503	.708
F	146.4451	3835.213	.757	.673	.836
Ca	86.6185	2433.208	.566	.532	.748
Mg	124.8925	2574.300	.863	.809	.677
Na	113.3244	2103.820	.683	.660	.705

Scale Statistics

Mean	Variance	Std. Deviation	N of Items
146.9247	3860.681	62.13438	5

Scale Reliability Test: Factor 2

Case Processing Summary

		N	%
Cases	Valid	60	100.0
	Excluded[a]	0	.0
	Total	60	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.426	.494	2

Item Statistics

	Mean	Std. Deviation	N
N	.1682	.21209	60
P	.0847	.11187	60

Inter-Item Correlation Matrix

	N	P
N	1.000	.328
P	.328	1.000

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
N	.0847	.013	.328	.108	.
P	.1682	.045	.328	.108	.

Scale Statistics

Mean	Variance	Std. Deviation	N of Items
.2529	.073	.27032	2

Annexure 5. Factor analysis results: Gampaha controlled area

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.482
Bartlett's Test of Sphericity	Approx. Chi-Square	215.211
	df	21
	Sig.	.000

Communalities

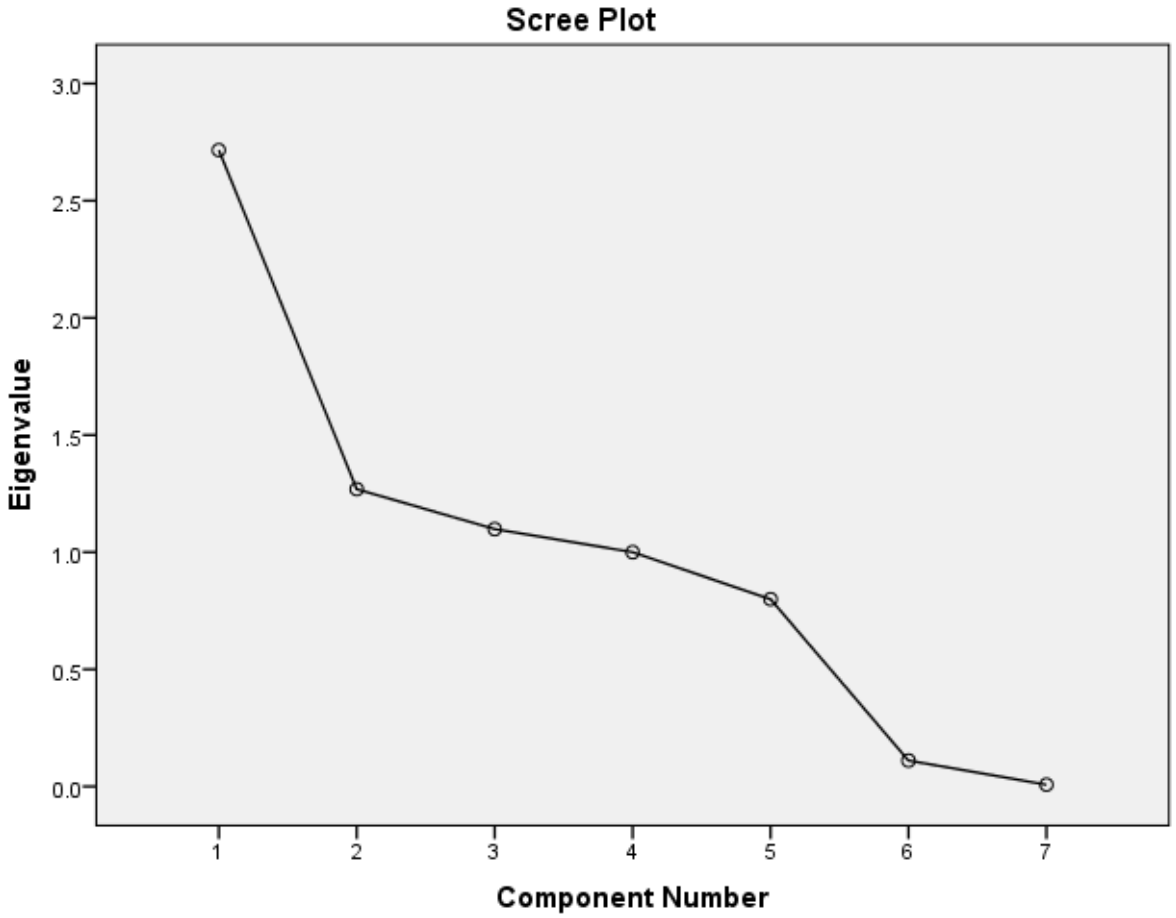
	Initial	Extraction
Cl	1.000	.966
F	1.000	1.000E-013
N	1.000	.830
P	1.000	.858
Ca	1.000	.583
Mg	1.000	.874
Na	1.000	.973

Extraction Method: Principal Component Analysis.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.716	38.799	38.799	2.716	38.799	38.799	2.289	32.699	32.699
2	1.269	18.124	56.924	1.269	18.124	56.924	1.581	22.592	55.291
3	1.098	15.691	72.615	1.098	15.691	72.615	1.213	17.324	72.615
4	1.000	14.286	86.900						
5	.799	11.415	98.315						
6	.111	1.580	99.895						
7	.007	.105	100.000						

Extraction Method: Principal Component Analysis.



Component Matrix[a]

	Component		
	1	2	3
Cl	.875	-.318	.314
F	.000	.000	.000
N	.852	.144	-.288
P	-.007	.694	.614
Ca	-.302	-.179	.678
Mg	.605	.707	-.092
Na	.876	-.366	.269

Extraction Method: Principal Component Analysis.

a. 3 components extracted.

Rotated Component Matrix[a]

	Component		
	1	2	3
Cl	.979	.084	-.022
F	.000	.000	.000
N	.561	.717	-.010
P	-.006	-.098	.921
Ca	.073	-.720	.243
Mg	.232	.723	.545
Na	.978	.093	-.087

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

a. Rotation converged in 5 iterations.

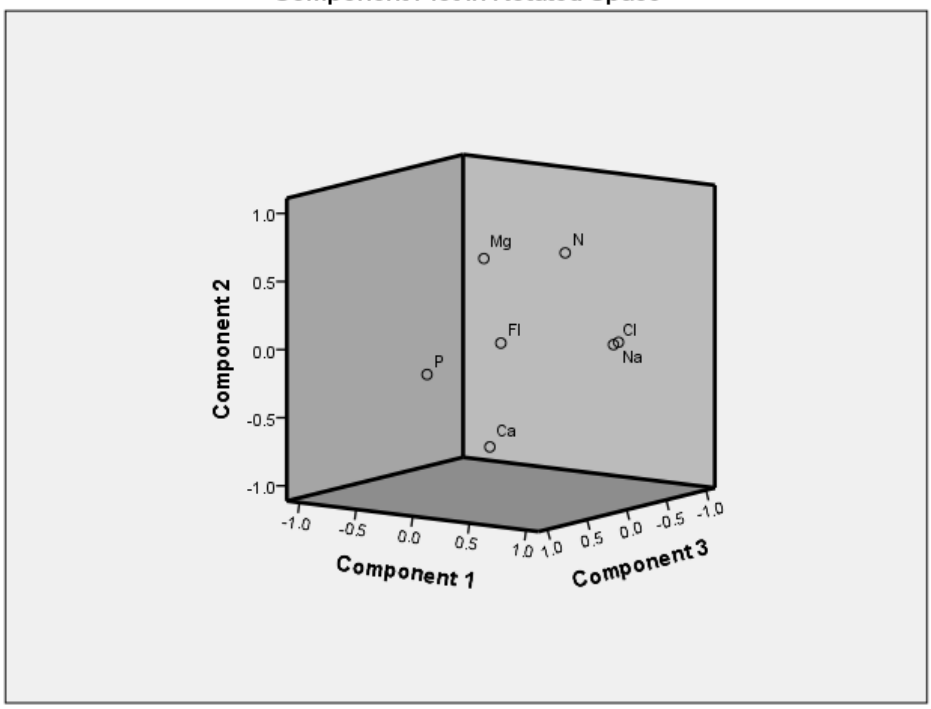
Component Transformation Matrix

Component	1	2	3
1	.850	.523	.054
2	-.349	.484	.802
3	.394	-.701	.594

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

Component Plot in Rotated Space



Scale Reliability Test: Factor 1

Case Processing Summary

		N	%
Cases	Valid	40	100.0
	Excluded[a]	0	.0
	Total	40	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.977	2

Scale Reliability Test: Factor 2

Case Processing Summary

		N	%
Cases	Valid	40	100.0
	Excluded[a]	0	.0
	Total	40	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha[a]	N of Items
-.363	3

a. The value is negative due to a negative average covariance among items. This violates reliability model assumptions. You may want to check item codings.

Annexure 6. Factor analysis results: Girandurukotte

Descriptive Statistics

	Mean	Std. Deviation	Analysis N
Cl	25.1222	22.26351	46
F	.6426	.50594	46
N	2.6500	2.45771	46
P	.3900	.27782	46
Ca	13.8080	9.36217	46
Mg	18.9826	18.57008	46
Na	22.8087	19.64189	46

Correlation Matrix[a]

		Cl	F	N	P	Ca	Mg	Na
Correlation	Cl	1.000	.030	.166	.228	.072	.234	.341
	F	.030	1.000	.003	.462	-.100	.370	.678
	N	.166	.003	1.000	.015	.020	.101	.048
	P	.228	.462	.015	1.000	-.124	.256	.514
	Ca	.072	-.100	.020	-.124	1.000	.166	-.011
	Mg	.234	.370	.101	.256	.166	1.000	.430
	Na	.341	.678	.048	.514	-.011	.430	1.000
Sig. (1-tailed)	Cl		.420	.135	.064	.316	.058	.010
	F	.420		.492	.001	.253	.006	.000
	N	.135	.492		.460	.447	.253	.375
	P	.064	.001	.460		.206	.043	.000
	Ca	.316	.253	.447	.206		.135	.471
	Mg	.058	.006	.253	.043	.135		.001
	Na	.010	.000	.375	.000	.471	.001	

a. Determinant = .216

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.661
Bartlett's Test of Sphericity	Approx. Chi-Square	64.183
	df	21
	Sig.	.000

Communalities

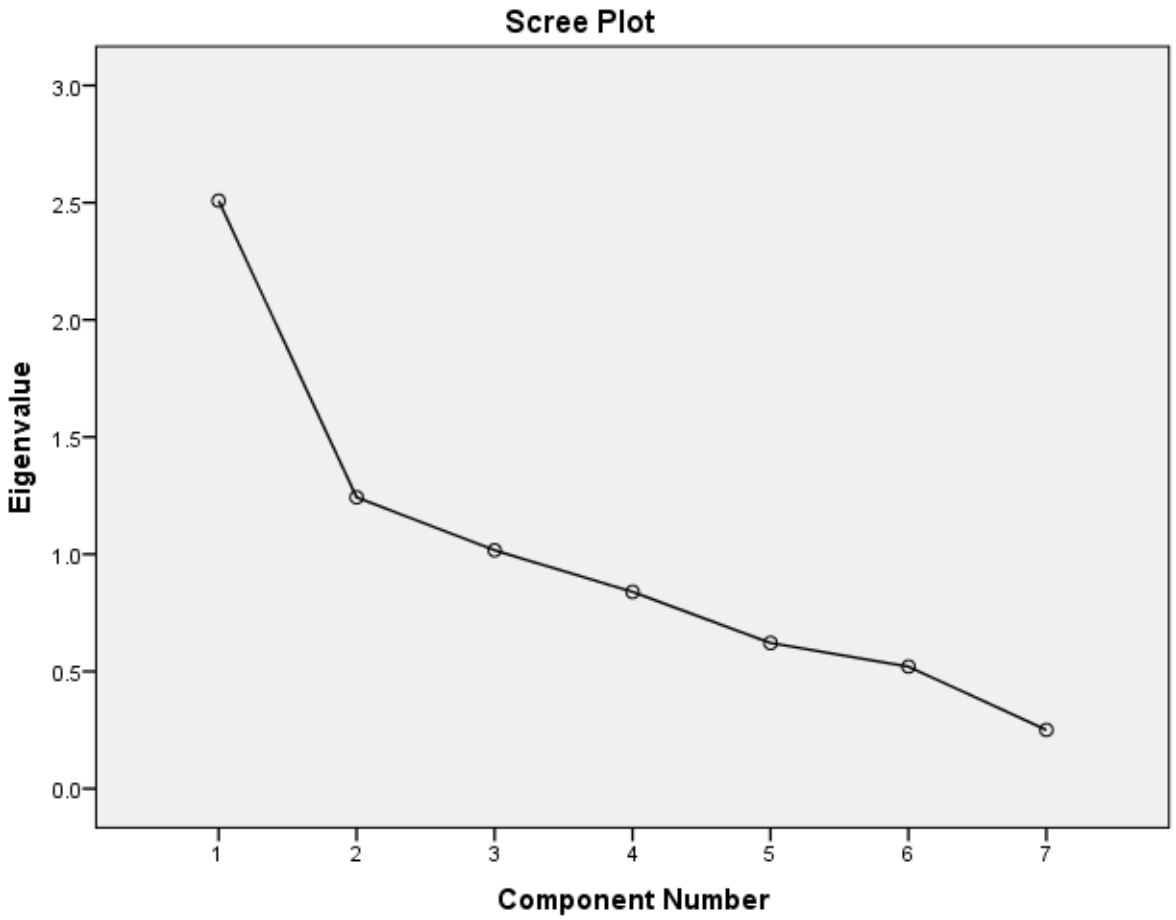
	Initial	Extraction
Cl	1.000	.551
F	1.000	.736
N	1.000	.692
P	1.000	.583
Ca	1.000	.844
Mg	1.000	.582
Na	1.000	.779

Extraction Method: Principal Component Analysis.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.508	35.834	35.834	2.508	35.834	35.834	2.402	34.307	34.307
2	1.243	17.755	53.589	1.243	17.755	53.589	1.218	17.407	51.714
3	1.017	14.528	68.117	1.017	14.528	68.117	1.148	16.403	68.117
4	.839	11.991	80.108						
5	.621	8.877	88.985						
6	.521	7.437	96.422						
7	.250	3.578	100.000						

Extraction Method: Principal Component Analysis.



Component Matrix[a]

	Component		
	1	2	3
Cl	.435	.514	
F	.781		
N		.509	-.646
P	.716		
Ca		.672	.626
Mg	.637		
Na	.880		

Extraction Method: Principal Component Analysis.

a. 3 components extracted.

Rotated Component Matrix[a]

	Component		
	1	2	3
Cl		.674	
F	.850		
N		.824	
P	.737		
Ca			.908
Mg	.552		.492
Na	.862		

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.[a]

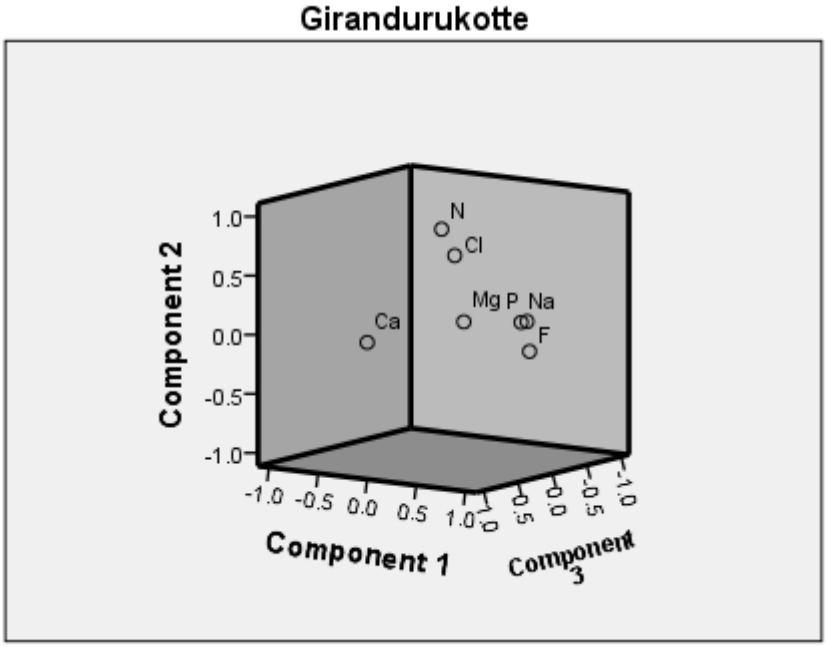
a. Rotation converged in 5 iterations.

Component Transformation Matrix

Component	1	2	3
1	.958	.261	.121
2	-.269	.666	.696
3	.101	-.699	.708

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.



Component Score Coefficient Matrix

	Component		
	1	2	3
Cl	.024	.536	.091
F	.383	-.187	-.052
N	-.126	.730	-.158
P	.312	.032	-.183
Ca	-.093	-.073	.811
Mg	.201	.050	.399
Na	.353	.028	.044

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

Component Score Covariance Matrix

Component	1	2	3
1	1.000	.000	.000
2	.000	1.000	.000
3	.000	.000	1.000

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

Scale Reliability Test: Factor 1

Case Processing Summary

		N	%
Cases	Valid	46	100.0
	Excluded[a]	0	.0
	Total	46	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.426	4

Item Statistics

	Mean	Std. Deviation	N
F	.6426	.50594	46
P	.3900	.27782	46
Mg	18.9826	18.57008	46
Na	22.8087	19.64189	46

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
F	42.1813	1052.805	.626	.459
P	42.4339	1065.156	.462	.471
Mg	23.8413	405.352	.433	.071
Na	20.0152	354.893	.450	.041

Scale Statistics

Mean	Variance	Std. Deviation	N of Items
42.8239	1073.611	32.76601	4

Scale Reliability Test: Factor 2

Case Processing Summary

		N	%
Cases	Valid	160	100.0
	Excluded[a]	0	.0
	Total	160	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha[a]	N of Items
.000	2

a. The value is negative due to a negative average covariance among items. This violates reliability model assumptions. You may want to check item codings.

Item Statistics

	Mean	Std. Deviation	N
N	2.3519	2.43953	160
Cl	97.0098	120.73980	160

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
N	97.0098	14578.098	-.006	.
Cl	2.3519	5.951	-.006	.

Scale Statistics

Mean	Variance	Std. Deviation	N of Items
99.3617	14580.439	120.74949	2

Scale Reliability Test: Factor 3

Case Processing Summary

		N	%
Cases	Valid	46	100.0
	Excluded[a]	0	.0
	Total	46	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.235	2

Item Statistics

	Mean	Std. Deviation	N
Ca	13.8080	9.36217	46
Mg	18.9826	18.57008	46

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
Ca	18.9826	344.848	.166	.
Mg	13.8080	87.650	.166	.

Scale Statistics

Mean	Variance	Std. Deviation	N of Items
32.7907	490.170	22.13977	2

Annexure 7. Factor analysis results: Huruluwewa

Descriptive Statistics

	Mean	Std. Deviation	Analysis N
Cl	144.6121	116.64969	29
F	.7183	.50100	29
N	1.0655	1.13083	29
P	.3148	.12894	29
Ca	29.6024	17.31709	29
Mg	188.8207	393.89659	29
Na	561.0828	543.04564	29

Correlation Matrix[a]

		Cl	F	N	P	Ca	Mg	Na
Correlation	Cl	1.000	-.307	.719	.127	.166	-.252	-.040
	F	-.307	1.000	-.458	-.039	.148	.456	.615
	N	.719	-.458	1.000	-.030	.236	-.334	-.271
	P	.127	-.039	-.030	1.000	.044	-.013	.044
	Ca	.166	.148	.236	.044	1.000	.003	-.013
	Mg	-.252	.456	-.334	-.013	.003	1.000	.303
	Na	-.040	.615	-.271	.044	-.013	.303	1.000
Sig. (1-tailed)	Cl		.053	.000	.255	.195	.094	.418
	F	.053		.006	.420	.222	.006	.000
	N	.000	.006		.439	.109	.038	.077
	P	.255	.420	.439		.410	.473	.410
	Ca	.195	.222	.109	.410		.493	.474
	Mg	.094	.006	.038	.473	.493		.055
	Na	.418	.000	.077	.410	.474	.055	

a. Determinant = .135

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.596
Bartlett's Test of Sphericity	Approx. Chi-Square	49.697
	df	21
	Sig.	.000

Communalities

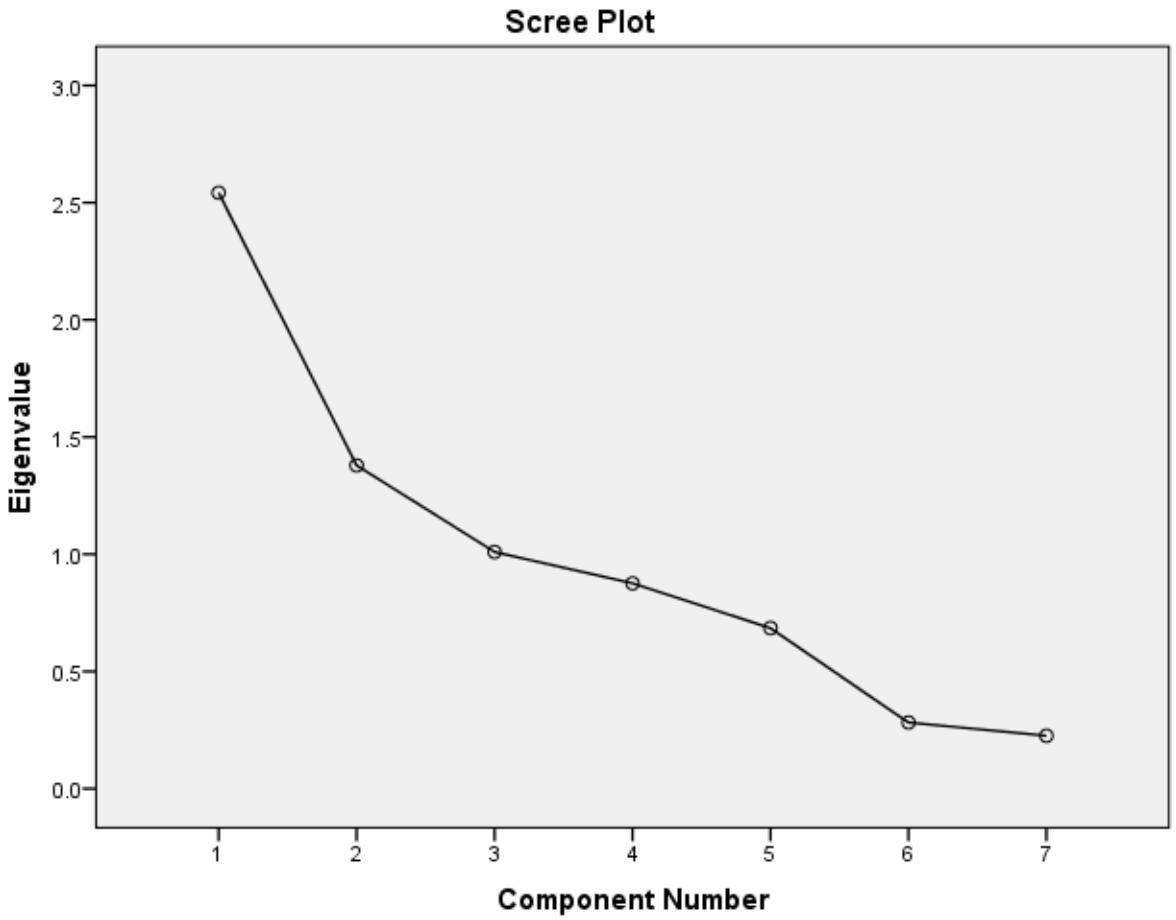
	Initial	Extraction
Cl	1.000	.759
F	1.000	.812
N	1.000	.827
P	1.000	.933
Ca	1.000	.513
Mg	1.000	.456
Na	1.000	.632

Extraction Method: Principal Component Analysis.

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.542	36.320	36.320	2.542	36.320	36.320	2.164	30.912	30.912
2	1.379	19.705	56.025	1.379	19.705	56.025	1.734	24.766	55.678
3	1.010	14.427	70.452	1.010	14.427	70.452	1.034	14.773	70.452
4	.876	12.513	82.965						
5	.685	9.783	92.748						
6	.282	4.030	96.778						
7	.226	3.222	100.000						

Extraction Method: Principal Component Analysis.



Component Matrix[a]

	Component		
	1	2	3
Cl	-.676	.546	
F	.795	.410	
N	-.814		
P			.935
Ca		.643	
Mg	.640		
Na	.603	.511	

Extraction Method: Principal Component Analysis.

a. 3 components extracted.

Rotated Component Matrix[a]

	Component		
	1	2	3
Cl		.802	
F	.892		
N	-.448	.792	
P			.965
Ca		.646	
Mg	.647		
Na	.779		

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.[a]

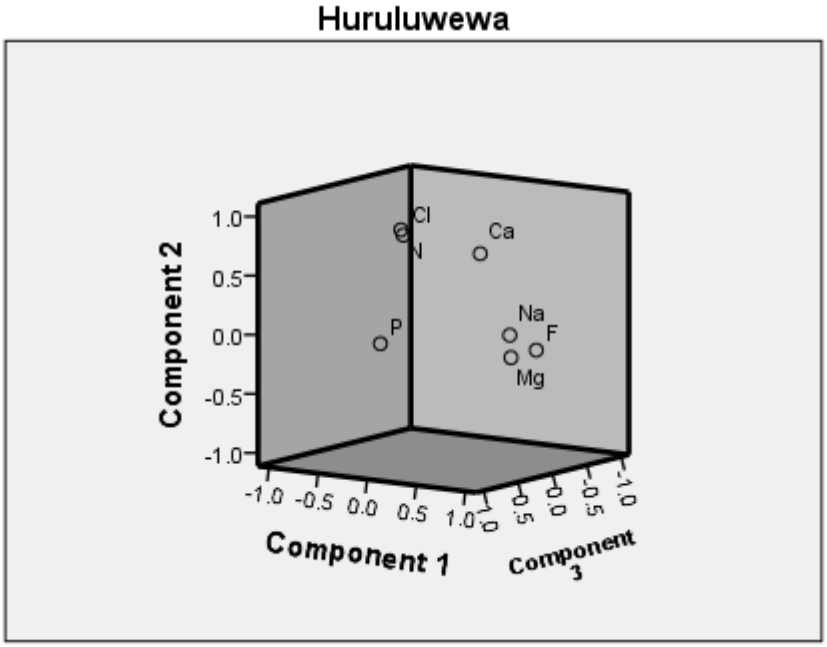
a. Rotation converged in 4 iterations.

Component Transformation Matrix

Component	1	2	3
1	.822	-.565	-.071
2	.566	.797	.212
3	-.063	-.214	.975

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.



Component Score Coefficient Matrix

	Component		
	1	2	3
Cl	.001	.451	.167
F	.432	.083	-.065
N	-.100	.430	-.074
P	.022	-.049	.940
Ca	.241	.461	-.177
Mg	.295	-.010	-.042
Na	.399	.143	.143

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

Component Score Covariance Matrix

Component	1	2	3
1	1.000	.000	.000
2	.000	1.000	.000
3	.000	.000	1.000

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.

Scale Reliability Test: Factor 1

Case Processing Summary

		N	%
Cases	Valid	29	100.0
	Excluded[a]	0	.0
	Total	29	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.336	3

Item Statistics

	Mean	Std. Deviation	N
F	.7183	.50100	29
Mg	188.8207	393.89659	29
Na	561.0828	543.04564	29

Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
F	749.9034	579621.842	.674	.447
Mg	561.8010	295233.406	.303	.002
Na	189.5390	155334.639	.303	.002

Scale Statistics

Mean	Variance	Std. Deviation	N of Items
750.6217	580136.548	761.66695	3

Scale Reliability Test: Factor 2

Case Processing Summary

		N	%
Cases	Valid	29	100.0
	Excluded[a]	0	.0
	Total	29	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.088	3

Item Statistics

	Mean	Std. Deviation	N
Cl	144.6121	116.64969	29
N	1.0655	1.13083	29
Ca	29.6024	17.31709	29

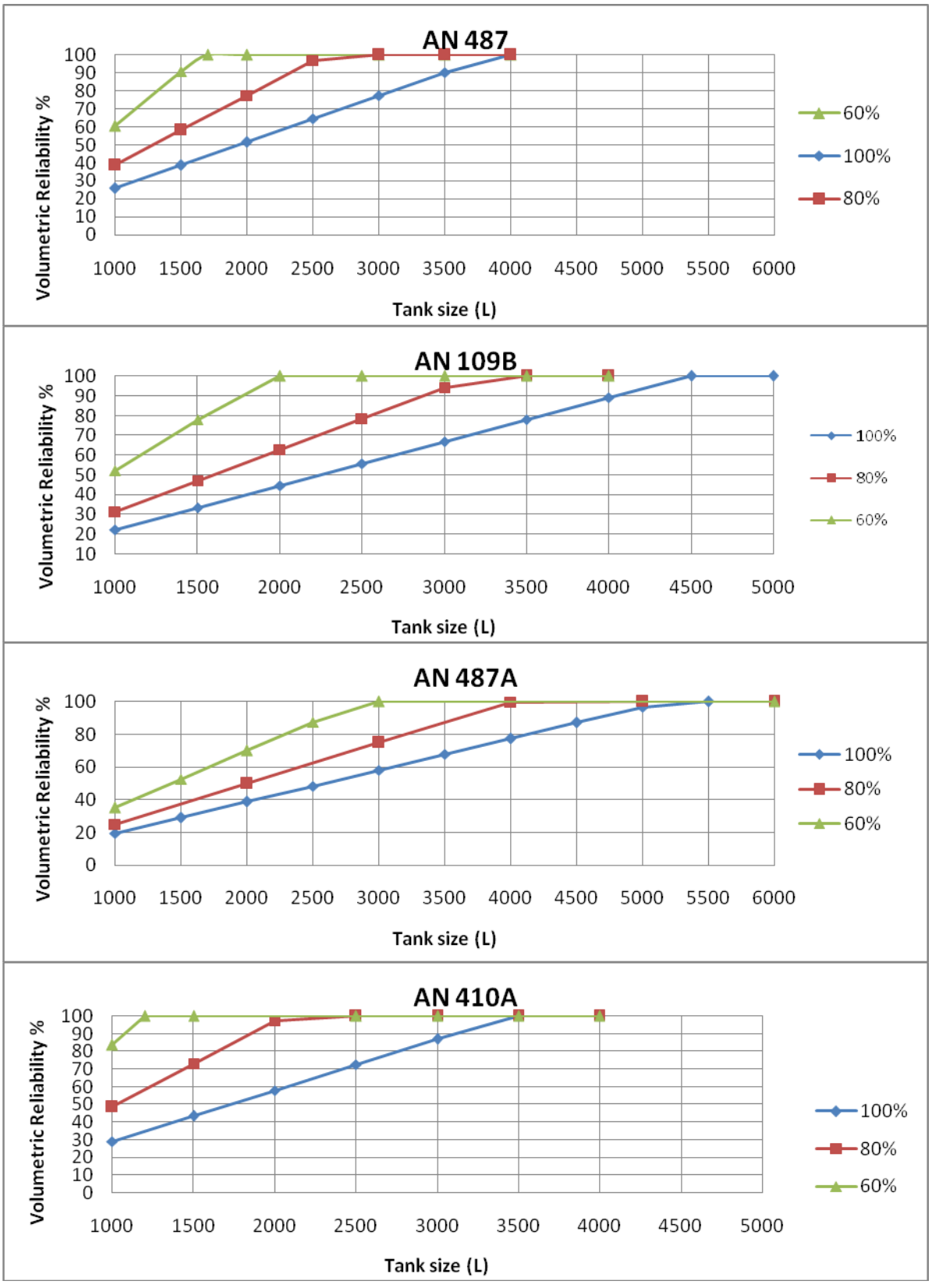
Item-Total Statistics

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
Cl	30.6679	310.402	.209	.060
N	174.2145	14577.748	.728	.092
Ca	145.6776	13798.062	.167	.027

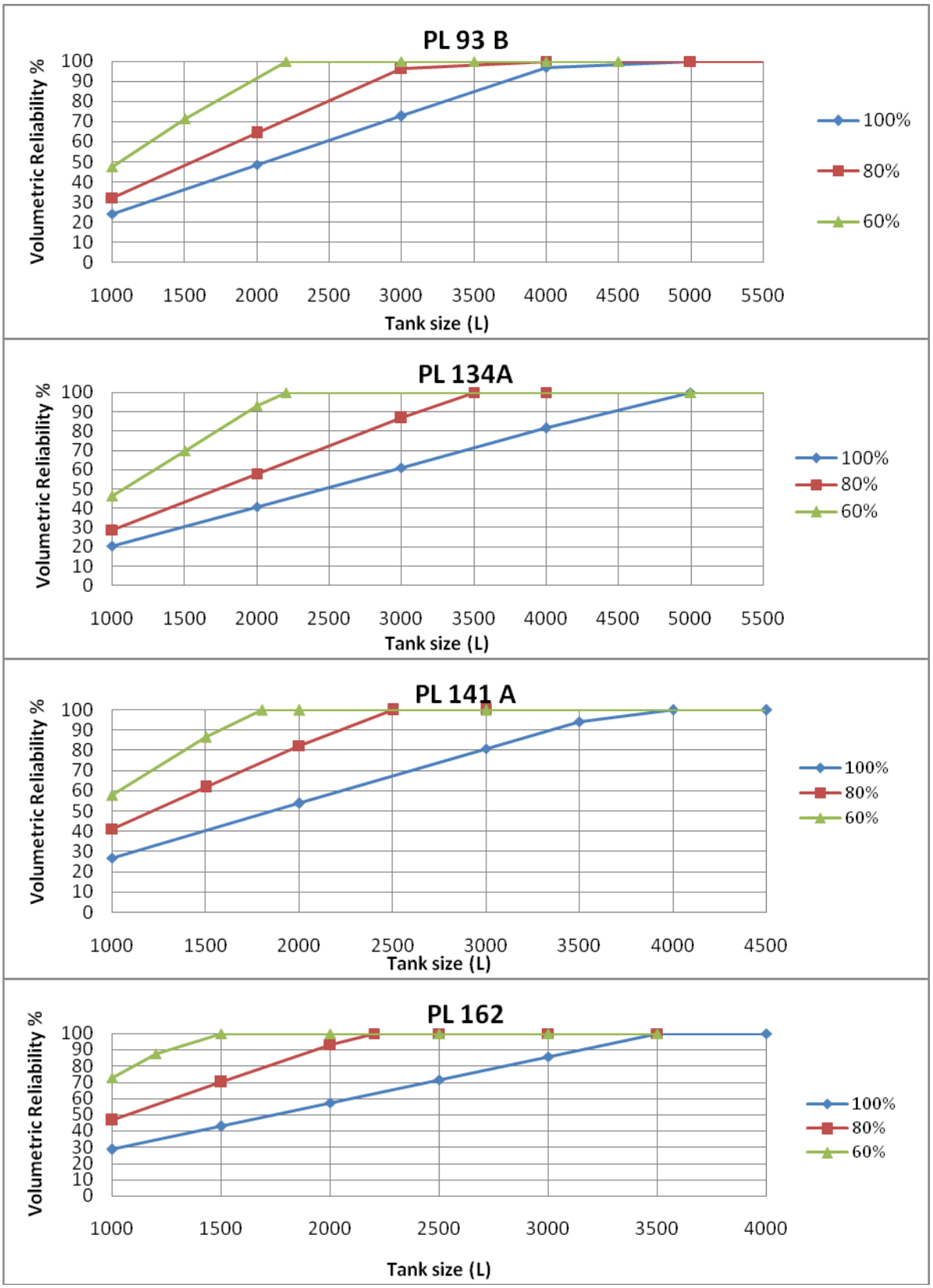
Scale Statistics

Mean	Variance	Std. Deviation	N of Items
175.2800	14777.901	121.56439	3

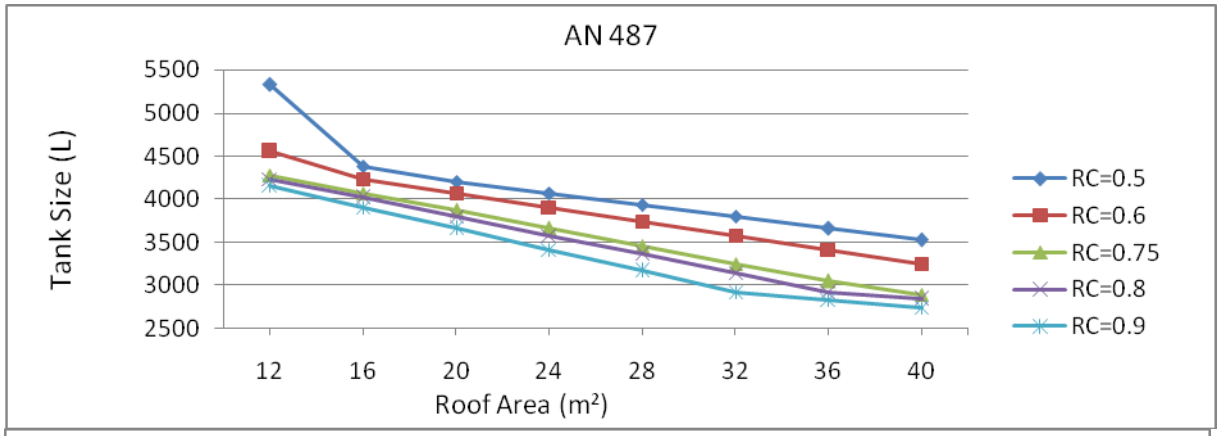
Annexure 8. Volumetric reliability of tanks estimated based on daily rainfall data for three different demand levels as a percentage of supply for stations in Anuradhapura

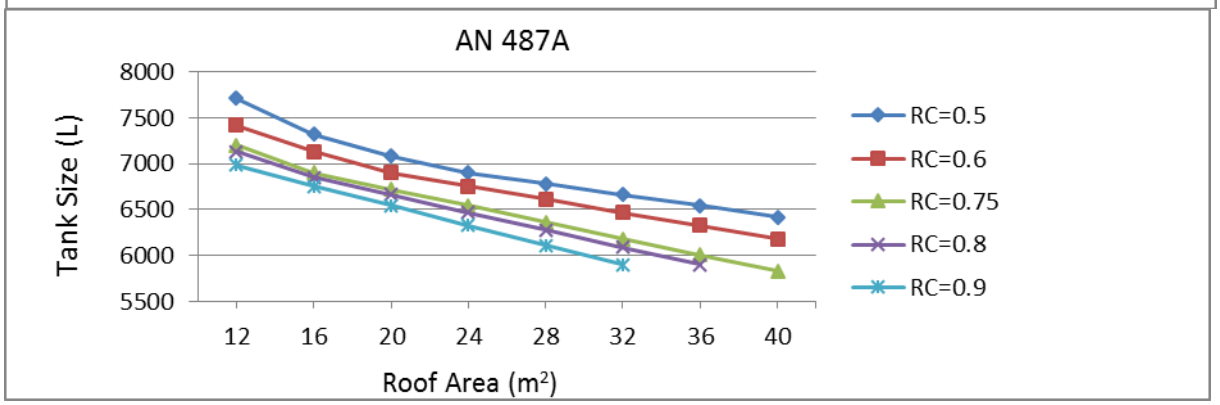


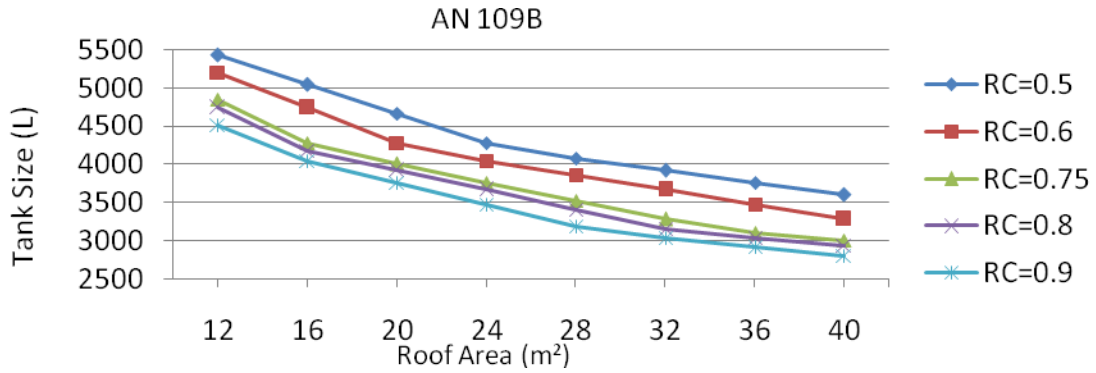
Annexure 9. Volumetric reliability of tanks estimated based on daily rainfall data for three different demand levels as a percentage of supply for stations in Polonnaruwa

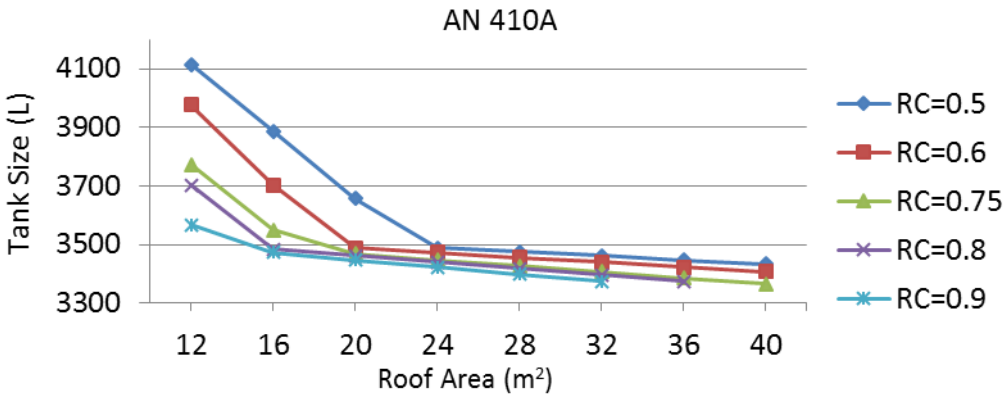


Annexure 10. The variation of tank sizes depending on the RC values when the household number (5 persons) and consumption per capita (6 L/day) are constants for Anuradhapura stations

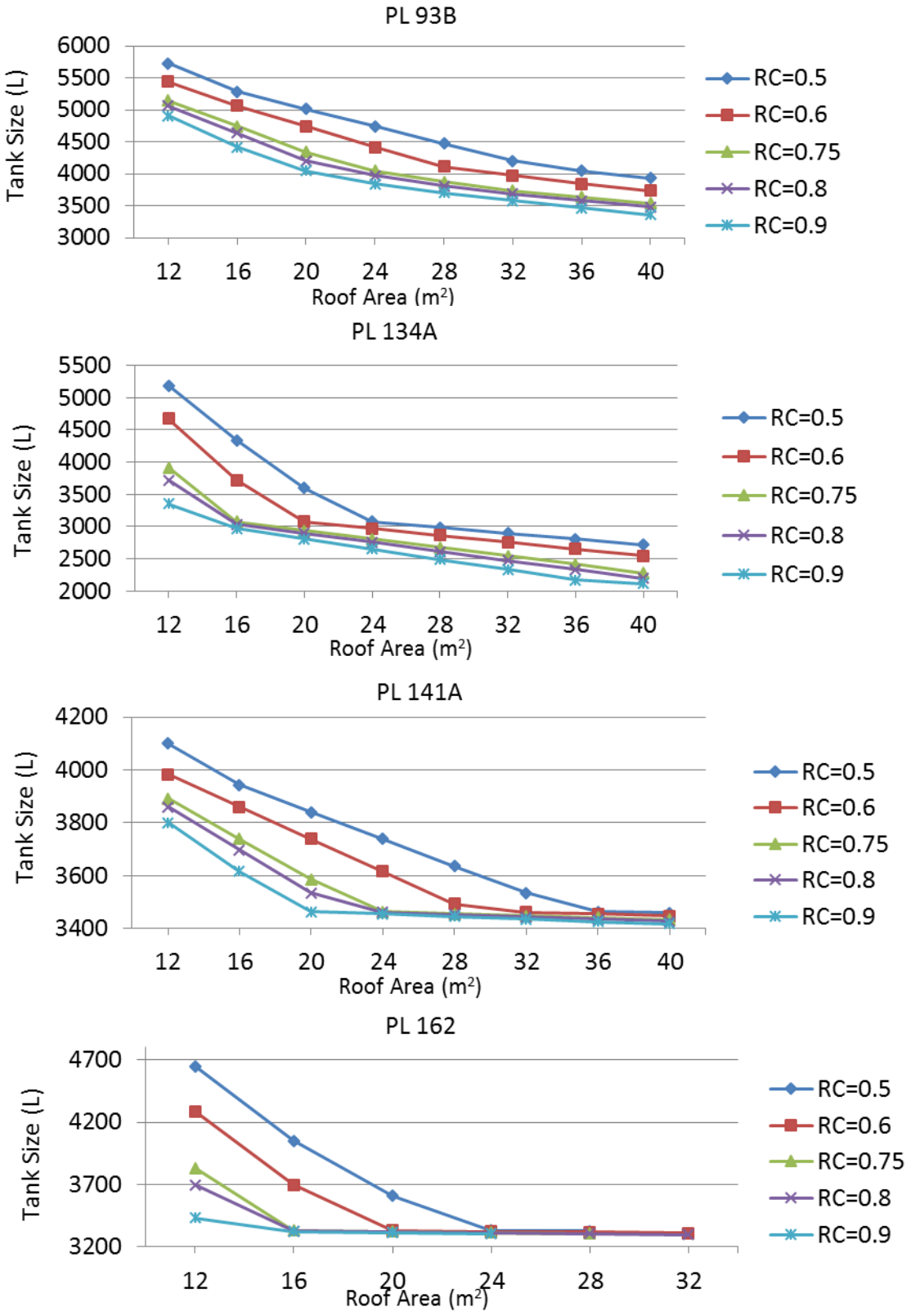




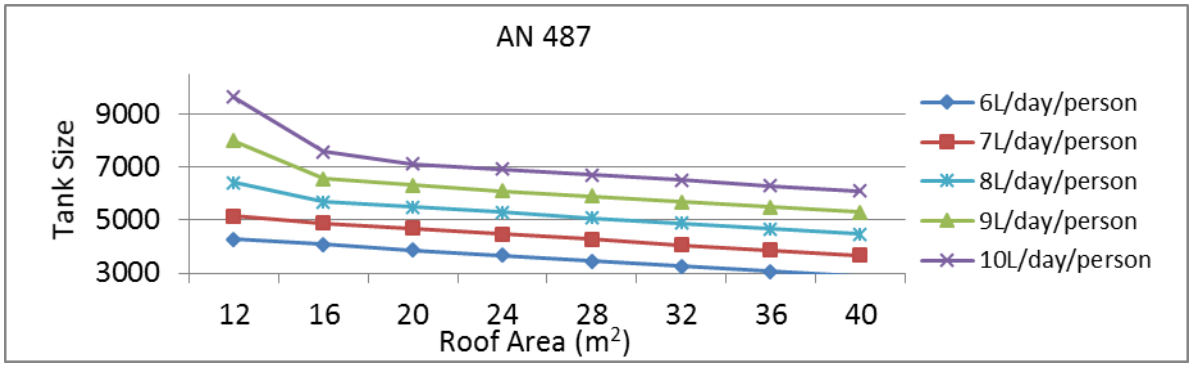


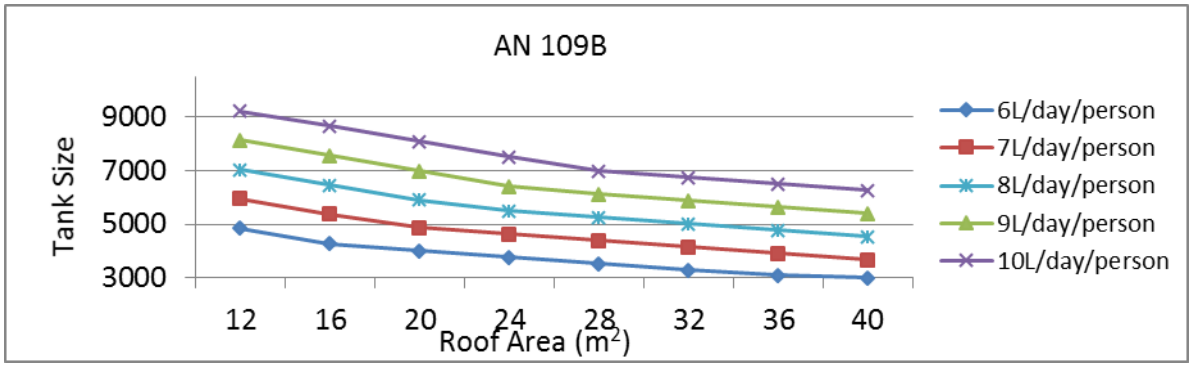


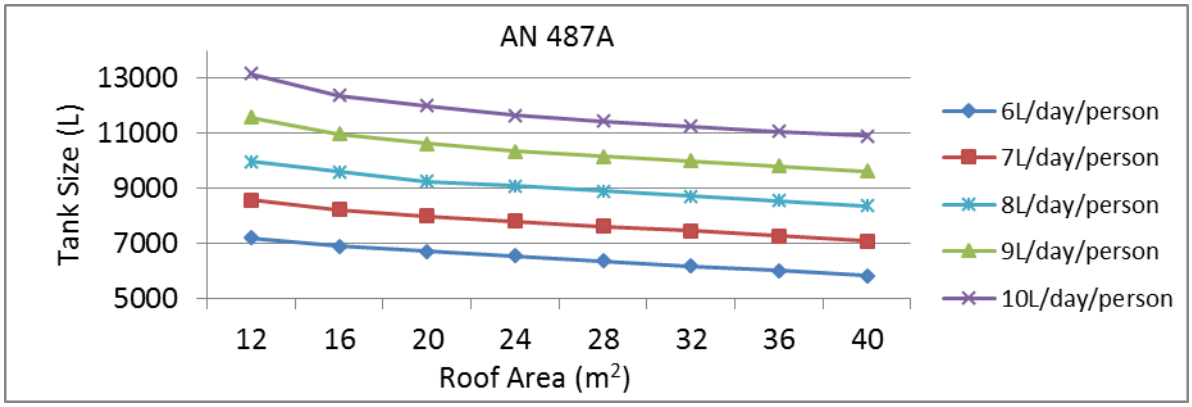
Annexure 11. The variation of tank sizes depending on the RC values when the household number (5 persons) and consumption per capita (6 L/day) are constants for Polonnaruwa stations

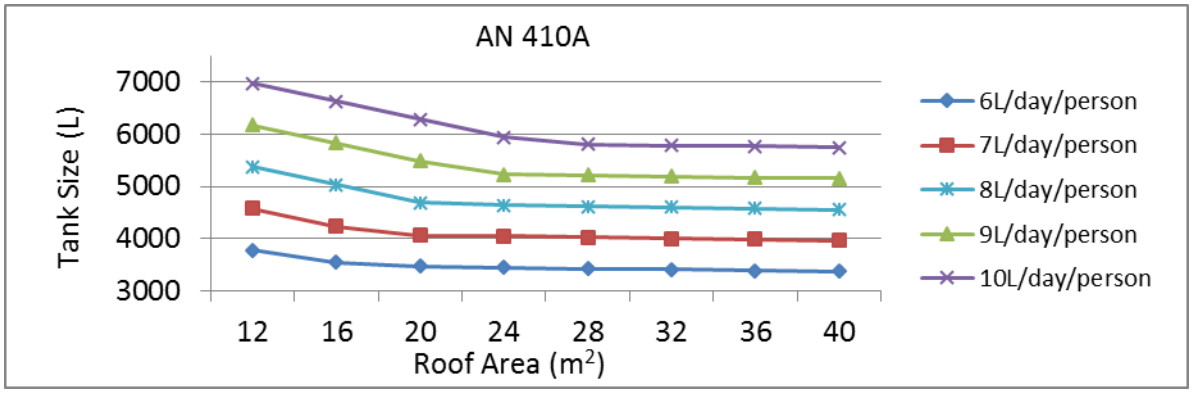


Annexure 12. The variation of tank sizes depending on per capita consumptions when the RC values (0.75) and household number (5 persons)) are constants for Anuradhapura stations

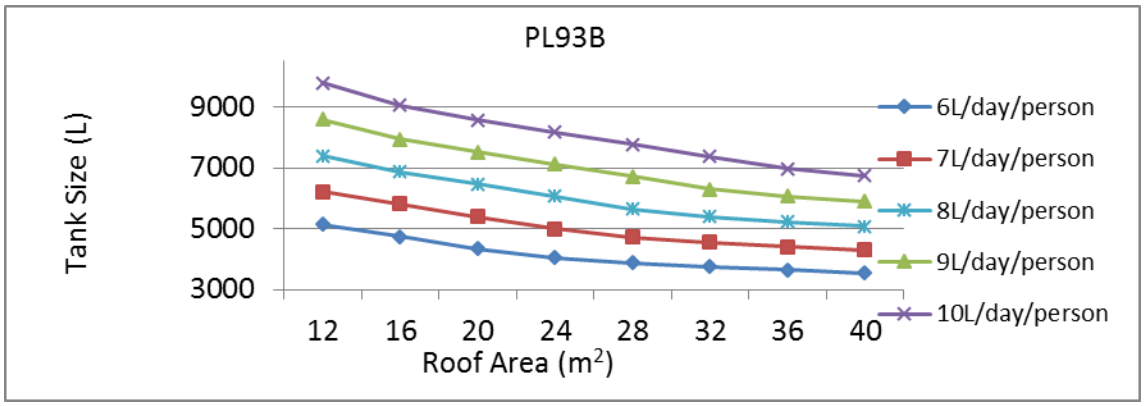


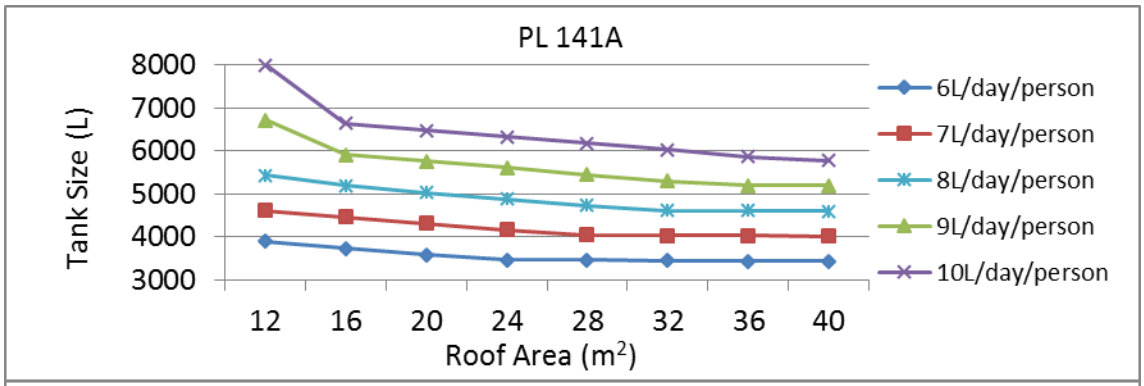


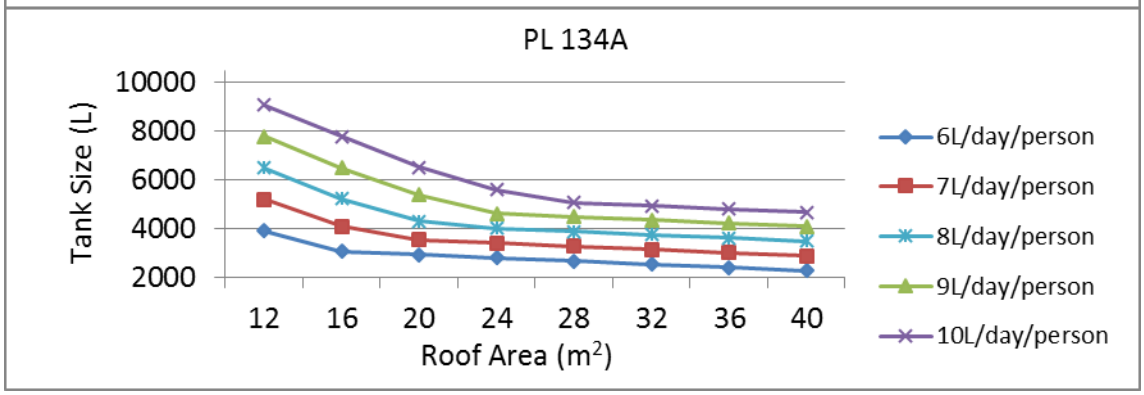


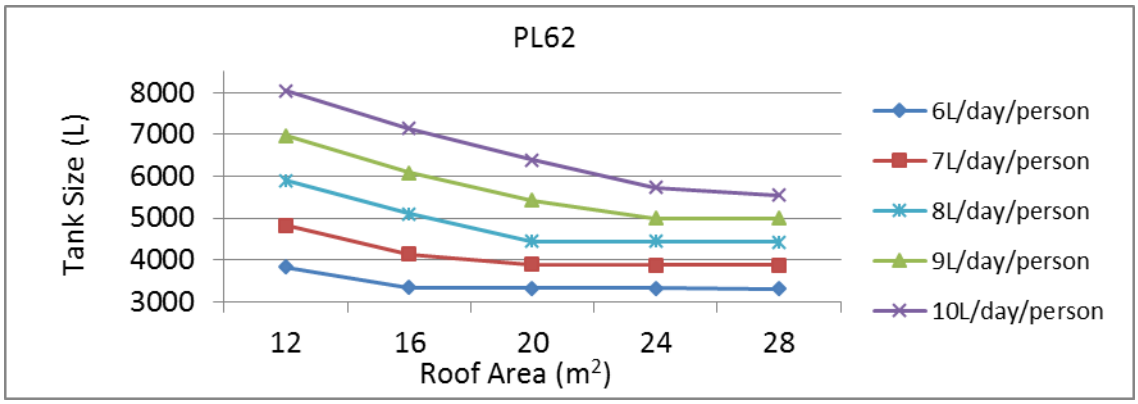


Annexure 13. The variation of tank sizes depending on per capita consumptions when the RC values (0.75) and household number (5 persons)) are constants for Polonnaruwa stations

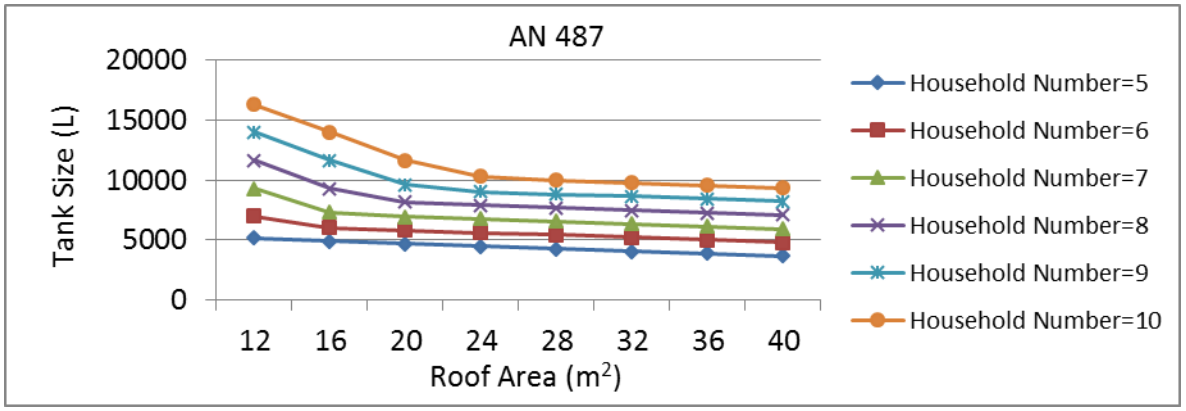


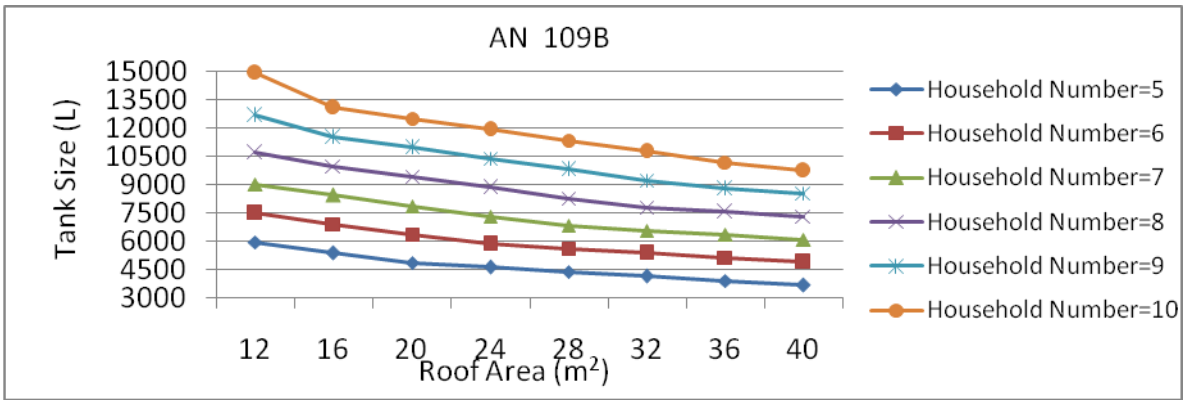


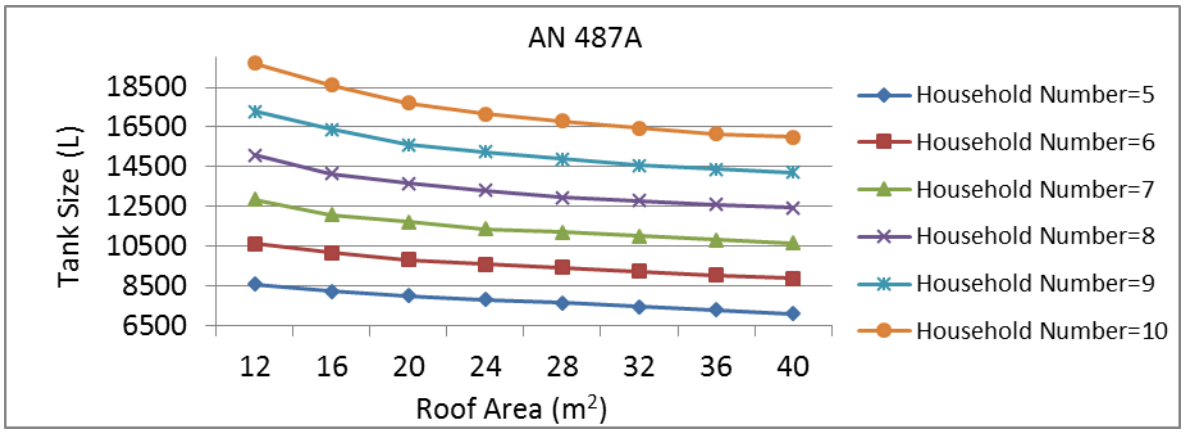


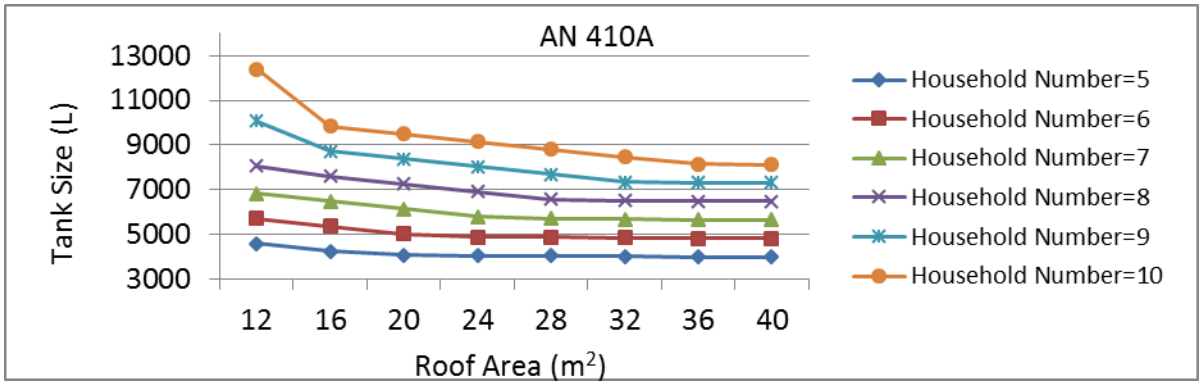


Annexure 14. The variation of tank sizes depending household numbers when the RC values (0.75) and on per capita consumptions (6 L/day/person) are constants for Anuradhapura stations

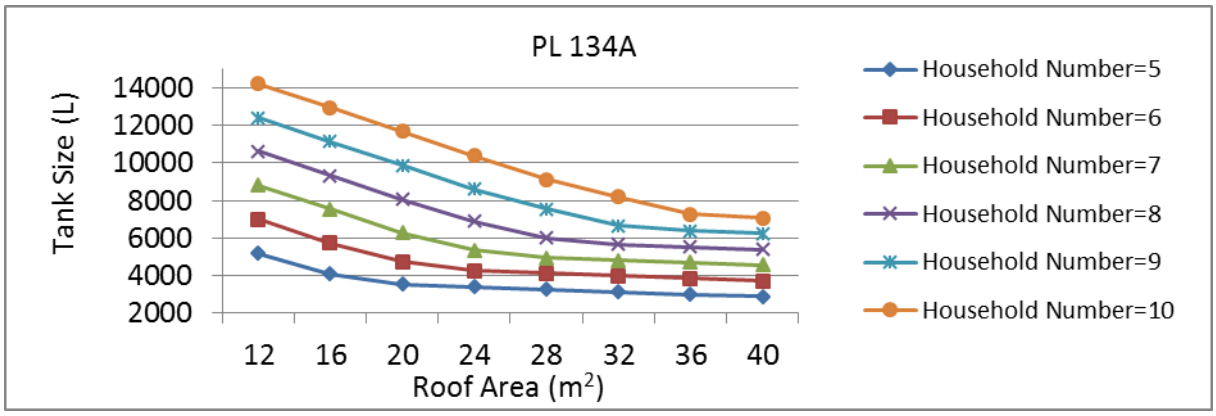


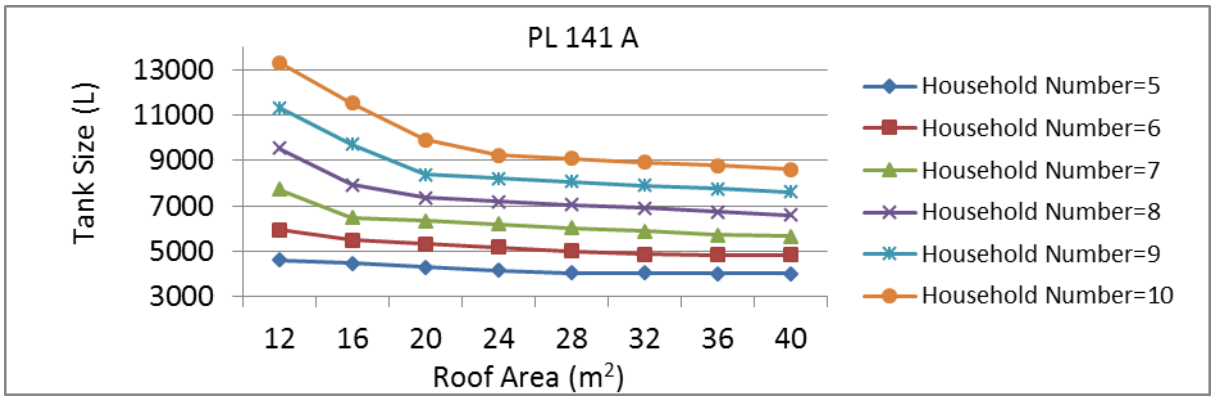


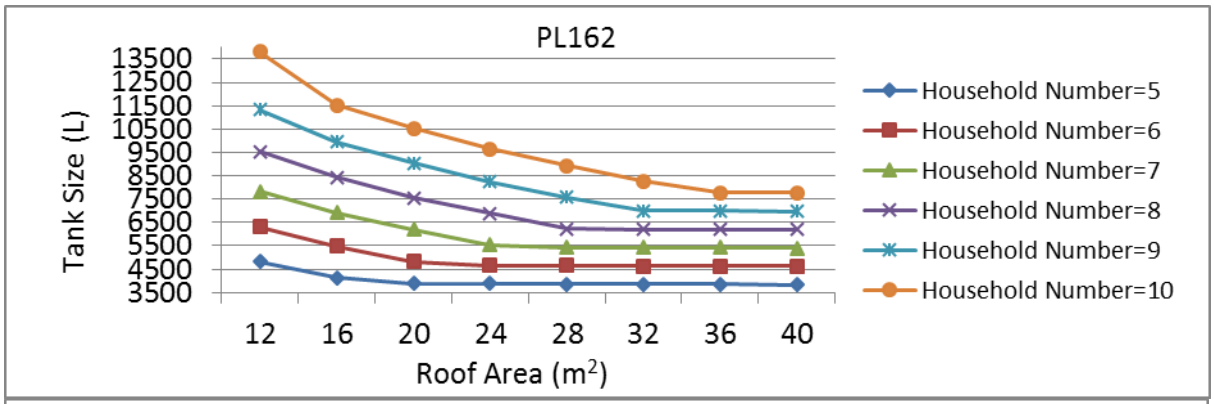


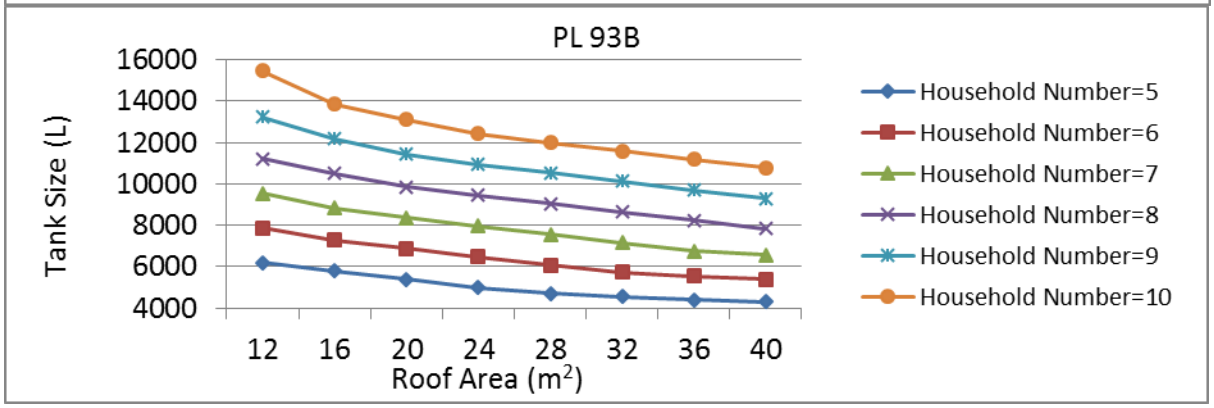


Annexure 15. The variation of tank sizes depending household numbers when the RC values (0.75) and on per capita consumptions (6 L/day/person) are constants for Polonnaruwa stations

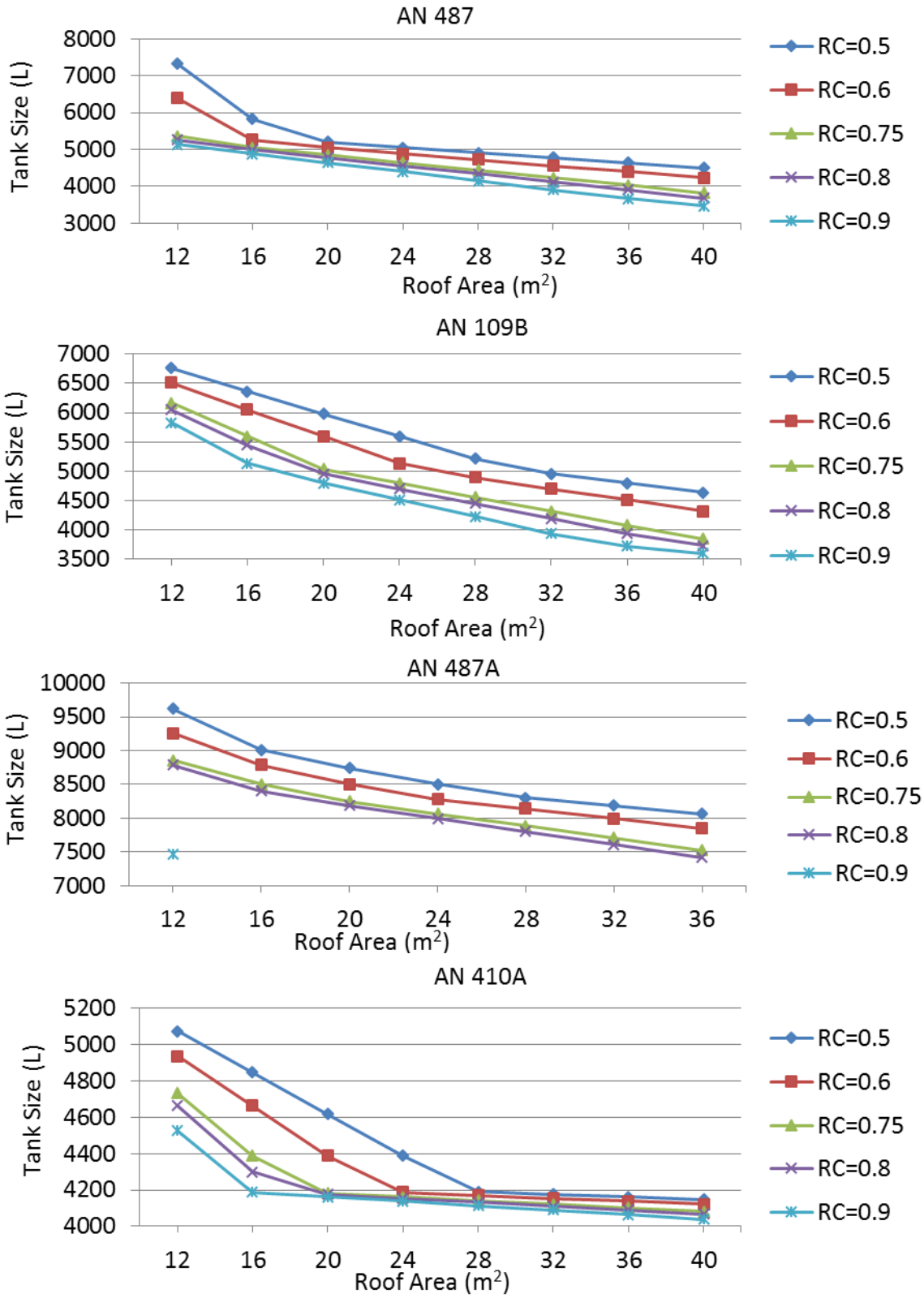








Annexure 16. The variation of tank sizes depending on RC values when per capita consumption (6L/day/person) and household number (6 person) are constants for Anuradhapura stations



Annexure 17. The variation of Tank sizes depending on RC values when per capita consumption (6L/day/person) and household number (6 person) are constants for Polonnaruwa stations